DEVELOPMENT OF AN INTEGRATED FIS-DEA METHOD FOR SUSTAINABLE SUPPLIER SELECTION IN MANUFACTURING

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Abstract

Supplier selection is an important area of decision making in manufacturing, especially for large and medium companies – either multinational (MNCs) or local. As sustainability in terms of preserving physical environment and developing long-term relationships between the partners in carrying out of manufacturing activities has gained world-wide focus, this dimension deserves due attention in selecting the competent suppliers in today's companies. Literatures show that the past researches done in this area didn't adequately discern and put the sustainable issues in a form of generic model. In real life applications, the importance of the various sustainable supplier selection criteria differ from one company to another and that depends on the circumstances where each organization may consider their relative importance for supplier selection criteria. The relative importance of the selection criteria and also the suppliers' performance with respect to these given criteria is to be established by the pertinent decision makers. Decision makers, however, normally prefer to answer these two scenarios (the weights of criteria and the suppliers' rating with respect to the criteria) in linguistic terms instead of being compared them numerically. So, the conventional supplier selection decision process involves a high degree of vagueness and ambiguity in practice.

This research takes the aforesaid issues into account, proposes a conceptual sustainable supplier selection model, and develops an integrated method based on Fuzzy Inference System (FIS) and Data Envelopment Analysis (DEA) theories for such supplier selection under uncertainty considering the relative importance of the performance indicators. The FIS-DEA method is designed so that the shortcomings of the conventional DEA approach (not being able to handle imprecise data, decision makers can freely choose the weights to be assigned to each input and output in a way that maximizes the efficiency, limitation on the number of inputs and outputs (criteria)

in accordance with the number of suppliers) could be eliminated. To handle the subjectivity of decision makers' preferences, the related data including the relative importance of criteria and the suppliers' performance with respect to these criteria are processed through fuzzy set theories. The processed data of suppliers' performance are then passed into modular FIS system to achieve the sustainability affinity indices of suppliers. Moreover, to get the supplier ranking results, these indices are fed into a DEA approach. The applicability and feasibility of the proposed FIS-DEA method is tested through two test beds, which have been designed based on experts' knowledge in two large companies from two different countries. The performance of the proposed FIS-DEA method is also assessed by comparing the results obtained with the existing supplier selection FIS-based method through error measurement criteria. The results show that the amounts of all error measurement criteria (such as mean squared error (MSE), root mean square error (RMSE), and mean absolute error (MAE)) are found to be very small. Among all, the biggest errors are found under RMSE calculations and these are 9.55 and 7.12 percent for the first and second test beds respectively. These are less than 10 percent (acceptable range is 0-10%) and that show the validity on acceptance of the proposed method. The proposed method is an open-ended approach to adapt any number of candidate suppliers as well as their selection criteria that might suit today's flexible manufacturing needs.

Abstrak

Pemilihan pembekal adalah satu bidang penting dalam proses membuat keputusan dalam sektor pembuatan, terutama bagi syarikat-syarikat besar dan sederhana - sama ada syarikat multinasional (MNC) atau tempatan. Sebagai kesinambungan dari segi memelihara alam sekitar fizikal dan membangunkan hubungan jangka panjang antara rakan kongsi dalam menjalankan aktiviti pembuatan telah mendapat tumpuan di seluruh dunia, dimensi ini memerlukan perhatian yang sewajarnya dalam memilih pembekal yang berwibawa dalam syarikat-syarikat hari ini. Kesusasteraan menunjukkan bahawa kajian lepas yang dilakukan di kawasan ini tidak cukup memahami dan meletakkan isu-isu yang berterusan dalam bentuk model generik. Dalam aplikasi kehidupan sebenar, kepentingan kriteria yang mampan pelbagai pemilihan pembekal berbeza dari satu syarikat ke syarikat lain dan bergantung kepada keadaan di mana setiap organisasi boleh mempertimbangkan kepentingan relatif mereka untuk kriteria pemilihan pembekal. Kepentingan relatif kriteria pemilihan dan juga prestasi pembekal berkenaan dengan kriteria yang diberikan adalah yang akan ditubuhkan oleh pembuat keputusan penting. Pembuat keputusan, bagaimanapun, biasanya lebih suka untuk menjawab kedua-dua senario (berat kriteria dan penilaian pembekal berkenaan dengan kriteria) dari segi bahasa dan bukannya berbanding mereka berangka. Jadi, pemilihan pembekal proses keputusan konvensional melibatkan tahap kekaburan dan kesamaran dalam amalan.

Kajian ini mengambil isu-isu yang dinyatakan di atas ke dalam akaun, mencadangkan yang mampan model pemilihan pembekal konsep, dan membangunkan kaedah bersepadu berdasarkan Sistem kesimpulan kabur (FIS) dan Data balutan Analisis (DEA) teori untuk pemilihan pembekal itu di bawah ketidakpastian mempertimbangkan kepentingan relatif petunjuk prestasi. Kaedah FIS-Lahirkan direka supaya kelemahan pendekatan DEA konvensional (tidak dapat mengendalikan data

tidak tepat, pembuat keputusan bebas boleh memilih berat untuk diberikan kepada setiap input dan output dengan cara yang memaksimumkan kecekapan, had pada bilangan input dan output (kriteria) mengikut bilangan pembekal) boleh dihapuskan. Untuk mengendalikan subjektiviti pembuat keputusan 'pilihan, data yang berkaitan termasuk kepentingan relatif kriteria dan pembekal prestasi berkenaan dengan kriteria ini diproses melalui teori set kabur. Data yang diproses prestasi pembekal yang kemudian berlalu ke dalam sistem FIS modular untuk mencapai indeks pertalian kemampanan pembekal. Selain itu, untuk mendapatkan keputusan ranking pembekal, indeks ini akan dimasukkan ke dalam satu pendekatan Lahirkan. Kesesuaian dan kemungkinan cadangan kaedah FIS-Lahirkan diuji melalui dua katil ujian, yang telah direka berdasarkan pengetahuan pakar-pakar 'dalam kedua-dua syarikat besar dari kedua-dua negara yang berbeza. Prestasi dicadangkan kaedah FIS-Lahirkan juga dinilai dengan membandingkan keputusan yang diperolehi dengan kaedah pemilihan pembekal FIS berasaskan sedia ada melalui kriteria pengukuran kesilapan. Keputusan menunjukkan bahawa jumlah semua kriteria pengukuran kesilapan (seperti ralat kuasa dua min (MSE), akar bermakna ralat kuasa dua (RMSE), dan min ralat mutlak (MAE)) didapati sangat kecil. Antara semua, kesilapan-kesilapan terbesar yang ditemui di bawah pengiraan RMSE dan ini adalah 9.55 dan 7.12 peratus bagi katil ujian pertama dan kedua. Ini adalah kurang daripada 10 peratus (julat boleh diterima adalah 0-10%) dan yang menunjukkan kesahihan pada penerimaan kaedah yang dicadangkan. Kaedah yang dicadangkan adalah satu pendekatan terbuka untuk menyesuaikan diri dengan apa-apa bilangan pembekal calon serta kriteria pemilihan mereka yang mungkin memenuhi keperluan pembuatan fleksibel hari ini.

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With best wishes to all of them

Atefeh Amindoust

Author

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List of Acronyms

$\mu\ (x_i)$	Degree of membership function related to *ith* element
a^l, a^m, a^u	The lower, medium, and upper part of a triangular fuzzy number
$\tilde{w}$	A triangular fuzzy number
x_{COA}	The deffuzzified output
y_{js}	The amount of output j provided by unit s
x_{ls}	The amount of input l provided by unit s
$u_j\ ,\ v_l$	The weights of outputs and inputs, respectively
Z_s	The efficiency s th of decision making unit
$\tilde{r}_{jk}$	The array of the supplier's performance matrix with respect to j th sub-criteria based on k th decision maker
sp_s	The supplier's performance matrix of s th supplier
R_s	The fuzzy decision matrix of s th supplier's performance
FDM	Fuzzy decision matrix of suppliers' performances
$\tilde{R}D_{sj}$	The aggregated arrays of s th supplier's performance with respect to j th sub-criteria
R_{jk}	The aggregated and defuzzified arrays of supplier's performance with respect to j th sub-criterion of k th decision maker
CD	The defuzzified matrix of all suppliers 'performances
$\tilde{w}c_{ik}$	The relative importance of i th criterion based on k th decision maker
$\tilde{w}sc_{ik}$	The relative importance of j th sub-criterion based on k th decision maker
wc	The relative importance of each criterion

wsc	The relative importance of each sub-criterion
fw	The multiplied matrix of the criteria and sub-criteria weights
$\tilde{W}_{ik}$	The aggregated arrays of fw matrix into i th criterion based on k th decision maker
FW	The aggregated matrix of fw matrix
W_{ik}	The defuzzified form of $\tilde{W}_{ik}$
CW	The defuzzified form of FW matrix
R_{CW^T}	The ratio matrix of criteria weights
$c_{i\times s}$	The i th affinity index for s th supplier
CAI	The related matrix into affinity indices of criteria for each supplier
WSC	The aggregated matrix of wsc for sub-criteria weights
$\tilde{x}_{n\times 1}$	The prepared inputs for the FIS-based method
WC	The aggregated criteria weights for each criterion
A_i	The experimental value which derived from the FIS-based method
F_i	The predicted value, which derived from the proposed FIS-DEA method

List of Abbreviations

MNCs	Multi-National Companies
NGOs	None Governmental Organizations
SCM	Supply Chain Management
DEA	Data Envelopment Analysis
DMUs	Decision Making Units
FIS	Fuzzy Inference System
FIS-DEA	Fuzzy Inference System-Data Envelopment Analysis
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ANN	Artificial Neural Network
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
ISM	Interpretive Structural Modeling
ANFIS	Adaptive Neuro-Fuzzy Inference System
SMART	Simple Multi Attribute Rating Technique
QFD	Quality Function Deployment
TFT-LCD	Thin Film Transistor Liquid Crystal Display
RoHS	Restriction of Hazardous Substances
EUP	Enterprise Unified Process
ISO	International Standard Organization
WEEE	Waste Electrical and Electronic Equipment
DEMATEL	Decision Making Trial and Evaluation Laboratory
CLSC	Closed-Loop Supplier Chain
FCM	Fuzzy Cognitive Map
SEM	Structural Equation Modeling
COA	Center of Area Method

BOA	Bisector of Area Method
MOM	Mean of Maximum Method
SOM	Smallest of Maximum Method
LOM	Largest of Maximum Method
DEA/AR	Assurance Region model of DEA
WI	Weak Importance
LMI	Low Moderate Importance
MI	Moderate Importance
SI	Strong Importance
EI	Extreme Importance
VWP	Very Weakly Preferred
WP	Weakly Preferred
LMP	Low Moderately Preferred
MP	Moderately Preferred
HMP	High Moderately Preferred
SP	Strongly Preferred
EP	Extremely Preferred
MSE	Mean-Squared Error
RMSE	Root MSE
MAE	Mean Absolute Error
CAI	Criteria Affinity Index
DM	Decision Maker

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CHAPTER 1

INTRODUCTION

This Chapter presents the background on the issues that are pertinent to the topic of this research. Supplier evaluation and selection is one of the most important decisions in today's manufacturing. This kind of decisions is basically designed on the extensive range of suppliers' performance indicators and decision making methods. These issues are appropriate for setting the background of the supplier selection problem. This thesis is presenting an integrated supplier selection method for deciding on the best probable suppliers considering the economic, social, and environmental aspects in sustainable manner to meet the current manufacturing needs.

A brief account on theoretical and practical relevance of the research is given in the following section. After this brief background, the research problem statement followed by research objectives, and scope and limitations are placed in this Chapter.

1.1 Background of the Research

In these days, people do not see a product from its price alone. Both manufacturer and customer are now more concerned about the life-cycle behavior and involvement of a product. In this realm, engineering or product designer cannot work in isolation but need to sit-together with other disciplines including the purchasing people. Purchasing management has come to play a critical role as a key to optimize the business activities in manufacturing under recent agile improvement of network technology, economic globalization, and growing of outsourcing agenda. Now a production plant need to fulfill a variety of agenda or criteria under the domains of economic, social, technological and environmental aspects. These together in long-term performance achievements come to the fold of sustainable manufacturing. One of the crucial challenges in manufacturing for purchasing department is supplier evaluation and henceforth their selection (Aissaoui et al., 2007) considering the sustainable agenda. Supplier selection is the process by which a group or large number of suppliers' performances and abilities are reviewed, evaluated, and chosen to become a part of company's supply chain. Basically, there are two kinds of supplier selection problem as multiple sourcing and single sourcing. In single sourcing, one supplier can satisfy all the buyer's needs and the management needs to make only one decision, which supplier is the best. However, the best is always cunning. Whereas in multiple sourcing as no supplier can satisfy all the buyer's requirements, more than one supplier has to be selected (Guneri et al., 2009). There is a host of factors that have caused the multiple sourcing shifts to a single sourcing or a reduced supplier base. First, multiple sourcing prevents suppliers from achieving the economies of scale based on order volume and learning curve effect. Second, multiple supplier system can be more expensive than a reduced supplier base. For instance, managing a large number of suppliers for a particular item directly increase costs, including the labor and order processing costs out of managing multiple source inventories. Moreover, multiple sourcing lowers the overall materials and other supplies quality level because of the increased variation in incoming quality among suppliers. Third, a reduced supplier base helps to eliminate mistrust between buyers and suppliers due to lack of communication. Fourth, worldwide competition forces the firms to find the best suppliers in the world (R.F. Saen, 2010). So, supplier selection is an important area of decision making in manufacturing, mainly for large and medium companies– either multinational (MNCs) or local.

Under the foretold scenario, in today's production or service systems, sustainable development has become a buzzword that received a lot of attentions by policy makers, the popular press, and journals in different scientific fields as an interdisciplinary issue. In this context, the idea of sustainable manufacturing is growing. In addition to the academic field, also communities, governments, businesses, international agencies, and non-governmental organizations (NGOs) are increasingly concerned with establishing a means to monitor the performance and to assess progress toward sustainable development (Buyukozkan & Çifçi, 2011). The first and foremost thrust of this comes to engineering or product design that later disseminated to other areas or levels. Literature shows that the concept of sustainability consists of three dimensions: the protection of the natural environment, the maintenance of economic vitality, and observance of specific social considerations (Posch & Steiner, 2006). During the last two decades, sustainability considerations have become a progressively significant issue in supply chain management (SCM) (Chaabane et al., 2012; Z. Wu & Pagell, 2011). There are some drivers to motivate manufacturing firms for involving sustainable goals in their supply chains. Legislation, increasing customer awareness about sustainable issues (Buyukozkan & Çifçi, 2011; C. H. Chu et al., 2009) and competitive advantages (Buyukozkan & Çifçi, 2011; Walker et al., 2008) are the most popular drivers to sustainability. Nevertheless, research in sustainable supplier selection, considering the majors aspects and criteria is still in nascent state. Sustainability includes a lot of qualitative and quantitative dimensions, where qualitative dimensions out pass the quantitative ones. Therefore, another important issue is the development or selection of methods for sustainable supplier selection taking into the account of all major sustainable dimensions or agenda. Therefore, the number of supplier selection criteria would be increased and there is a need to adapt any number of supplier selection criteria and candidate suppliers for today's manufacturing including small, medium and large enterprises. This work is taking into accounts of these matters and proposed an open-ended supplier selection by integrating FIS and DEA methods.

1.2 Problem Statement for the Research

The problems in supplier selection process that deserves research focus are as follows:

- As sustainability in terms of maintaining physical environment and developing long-term relationship has gained world-wide focus in carrying out of manufacturing or service activities, this dimension deserves due attention in selecting supplier in today's companies. Thus far, economic aspects have received the highest attention from both suppliers and manufacturers in selecting suppliers in manufacturing. Sustainability is a comprehensive term and it comes from concurrent and vibrant presence of all aspects pertaining to economic, environmental, and social issues. Although literatures show that many works have been carried out in supplier selection, but only a few of them has paid attention on sustainable aspects that are also recent (AydIn Keskin et al., 2010; Kuo et al., 2010). So, considering or integrating all aspects under economic, environmental, and social is still left undone. Sustainability issues have so far not yet received due research attention in supplier selection decision process. Therefore, further research is necessary for coming up with a sustainable supplier selection model.
- Since multiple criteria are involved in supplier selection problem, an extensive range of multi-criteria decision making methods have been applied for supplier selection. In real life applications, the significance of criteria is different and depends on the circumstances and situations and each organization may consider its individual relative importance for criteria to select the best suppliers. In spite of this,

many publications on supplier selection have not taken it into account and the weights of criteria are considered same in the selection process (Carrera & Mayorga, 2008; Ha & Krishnan, 2008; L. Li & Zabinsky, 2011; R.F. Saen, 2008b; Sawik, 2010). In fact, different criteria have different levels of significance. So to do supplier selection in proper manner consideration of relative importance of criteria based on real-world information is unavoidable. This issue deserves research attention and analysis.

- The relative importance of the criteria and also the suppliers' performance with respect to these criteria should be verified with the relevant decision makers. Decision makers normally prefer to answer the questions in linguistic terms instead of numerical form (Büyüközkan & Çifçi, 2012; Shaw et al., 2012). But very often, they are obligated to answer the qualitative questions in quantitative form. Therefore, the subjectivity of human assessments is missed. Linguistic term is simple and tangible for them to express their perceptions. This might be a way of securing the company's information. So, the supplier selection decision is involved a high degree of vagueness and ambiguity in nature and uncertainty would be inevitable in supplier selection. This issue may be resolved by a further research.
- One methods of data analysis and decision making is DEA. It is one of the most used standalone techniques in supplier selection until 2008 (Falagario et al., 2012; W. Ho et al., 2010). However, going through literature and verifying the existing supplier selection methods, it is found that DEA-based methods with aforesaid issues have not received enough attention from researchers in recent years. This is because of the three-fold shortcomings of DEA technique. First, DEA cannot handle with imprecise and fuzzy data. The related data which divided into inputs and outputs in DEA must be numeric and precise. Second, in

original DEA formulations the assessed decision making units (DMUs) can freely choose the weights or values to be assigned to each input and output in a way that maximizes its efficiency, subject to this system of weights being feasible for all other DMUs. This freedom of choice shows the DMU in the best possible light, and is equivalent to assuming that no input or output is more important than any other. The free imputation of input–output values can be seen as an advantage, especially as far as the identification of inefficiency is concerned. If a DMU (supplier) is free to choose its own value system and some other supplier uses this same value system to show that the first supplier is not efficient, then a stronger statement is being made. The advantages of full flexibility in identifying inefficiency can be seen as disadvantages in the identification of efficiency. An efficient supplier may become efficient by assigning a zero weight to the inputs and/or outputs on which its performance is worst. This might not be acceptable by decision makers as well as by an analyst, who after spending time in a careful selection of inputs and outputs sees some of them being completely neglected by suppliers. Decision makers may have in supplier selection problems value judgments that can be formalized a priori and therefore should be taken into account in supplier selection. These value judgments can reflect known information about how the criteria used by the suppliers behave, and/or ‘‘accepted” beliefs or preferences on the relative worth of inputs, outputs or even suppliers. For example, in supplier selection problem in general, one input (material price) usually overwhelms all other inputs, and ignoring this aspect may lead to biased efficiency results. Suppliers might also supply some outputs that require considerably more resources than others and this marginal rate of substitution between outputs should somehow be taken into account when selecting a supplier(R.F. Saen, 2010). To avoid the problem of free (and often undesirable) specialization, input and output weights should be constrained in DEA and the assurance region models of DEA technique would be applied (Thompson et al., 1990). However, the assurance region models can be implemented for decision makings which may involve small number of inputs and outputs. Third, there is a limitation on the number of inputs and outputs (criteria) in accordance with the number of decision making units (suppliers) in DEA technique. The constraint is that there should be at least twice as many suppliers as there are inputs and outputs (criteria) combined (Dyson et al., 2001). If this is not the case then the likelihood of most or all suppliers receiving efficiency scores at or near 1.0 is great and this limits the discrimination power of the DEA. Under the foresaid drawbacks, centralizing on DEA technique and integration of it with other theories would be taken into account to pave a way to research objectives in supplier selection problem.

1.3 Objectives of the Research

The aim of this research is to propose a new decision model for sustainable supplier selection in manufacturing (and also possible to be in services) and introduce an integrated method by combining the fuzzy inference system (FIS) and data envelopment analysis (DEA) theories. The specific objectives of the research are as follows:

- To propose a conceptual sustainable supplier selection model by incorporating all the main criteria that could be generic in nature to be apt for manufacturing as well as service industries.
- To develop an FIS-DEA based integrated method for sustainable supplier selection under fuzzy environments considering the relative importance of the

performance indicators that would be able to incorporate decision makers' objectives in reliable manners.

- To propose an open-ended multi-criteria decision making method to solve the supplier selection problem with any number of suppliers and performance indicators.
- To investigate the performances of the proposed FIS-DEA method and compare that with the existing FIS-based supplier selection method.
- To investigate the performances of the proposed FIS-DEA method and compare that with the existing DEA-based supplier selection method.

1.4 Scope and Limitation of the Research

Considerable research attention by academics/researchers has emphasized on supplier selection problem in manufacturing. Due to the increasing growth of sustainability issues in supply chain management (SCM), working on sustainable supplier selection is not adequate and still undone. In the wide range of multi-criteria decision making methods for supplier selection, two aspects (viz. considering the weights of performance indicators, uncertain environments) have received much attention in recent years. However, there is a lack of emphasis on decision models those incorporated the sustainability issue with the two unavoidable aspects (viz. considering the weights of performance indicators, uncertain environments) in the selection process.

Thus the scope of this research is to develop decision model for sustainable supplier selection under uncertainty considering the relative importance of performance indicators. The proposed model is open-ended and applicable to any number of performance indicators and suppliers in any kind of manufacturing firms. In addition, there is a limitation for this research. To execute the proposed FIS-DEA method, a few number of performance indicators is not sufficient. Since the appropriate real life application could not be found in this research, the applicability and feasibility of the proposed method is tested through two test beds which are designed based on experts' knowledge from two different companies.

1.5 Contribution of the Research

This research has developed a generic decision making model for sustainable supplier selection for manufacturing and service firms, applicable for medium and large industries, where the sustainability in terms of economic, environmental, and social aspects are significant concerns. In the proposed model, there is no limitation on the number of suppliers, the number of performance indicators, and the relation between these two numbers. In fact, the results of this study can be used for companies those are having problems in a supplier selection system when related information is imprecise. Also, incorporation of relative importance of performance indicators will provide added benefits to the decision model that support manufacturing or service firms in the supplier selection process.

The main idea of this research has been published in a tier one (Q1) journal from the renowned Elsevier science direct house. A few more journal and international conference papers have been published and submitted on the various aspects of the research (see Appendix-J).

1.6 Organization of the Thesis

As seen earlier, Chapter 1 figured out the research background, problem statements, objectives and scope of the research work.

In Chapter 2, the literature on the supplier selection problem has been reviewed with focus to the sustainable suppliers' selection performance indicators and the methods therein until date. This chapter has been concluded by summarizing the gaps in the past works and pointing the potential for future research viewing the sustainability and of various supplier selection methods. Therefore, some research directions have been derived for this work. Finally, the theoretical bases that can be used in order to complete a research project are explained.

In Chapter 3, the methodologies that have been used to complete this research work are described. The readers can also see the methods of the data collection and the definition of data analysis in terms of test bed.

In Chapter 4, a model has been proposed on sustainable supplier selection. Thereafter, a proposed analytical supplier selection method based on FIS and DEA theories has been described. Finally, the existing FIS-based supplier selection method has been clarified to compare the proposed FIS-DEA method.

The feasibility and applicability of the proposed method are investigated and tested through two test beds in Chapter 5. The impacts and implications of contributions of the proposed method are examined and described in this chapter.

In Chapter 6, this thesis has been concluded and the future research directions have been suggested for further advancement of this work.

CHAPTER 2

LITERATURE REVIEW

In recent years, the literature in supply chain management (SCM) in manufacturing industries presents the exponential growth in the number of publications which involved in supplier selection issues. The starting point to develop formal vendor selection systems is known as Dickson's analysis of supplier selection (Dickson, 1966). After that, an extensive range of models have been applied in making decision on supplier selection. There are at least five journal articles reviewing the literature regarding supplier evaluation and selection models (de Boer et al., 2001; Degraeve et al., 2000; W. Ho et al., 2010; Holt, 1998; Weber et al., 1991). Since these 5 articles review the literature up to 2008, this chapter extends them through a literature review and taxonomy of the 90 international journal articles between 2008 and 2012 to map out the supplier selection issue and to recommend the research gaps.

2.1 Supplier Selection Indicators and Methods

This section is done based on the two important questions which involved in supplier selection problem including "which supplier performance indicators" and "which supplier selection methods" would be considered in the selection process. So, the existing suppliers' performance indicators and supplier selection methods in manufacturing are derived through extensive literature review in this section to find research gaps. Due to the nature of supplier selection which deals with multiple criteria, researches thus far have been applied multi-criteria decision making methods, such as analytic hierarchy process (AHP), analytic network process (ANP), artificial neural network(ANN), data envelopment analysis(DEA), fuzzy set theory, mathematical programming, technique for order preference by similarity to ideal solution(TOPSIS), and their hybrids. Having a look at supplier selection papers, it is found that two aspects have received more attentions. Firstly, the relative importance issue of the performance indicators was concentrated a lot. Secondly, supplier selection decision under fuzzy data has been received a lot. So, the supplier selection problem here is supported from these two dimensions and the existing methods are combined into four categories which are briefed in the following sub-sections. Also, the performance indicators used in the approaches and applications of the proposed approaches are included in these sub-sections.

2.1.1 Selection Methods with the consideration of Indicators' Weights

Seventeen out of ninety articles (18.9%) have considered the relative importance of supplier performance indicators in their methods. The related information to these articles including the applied methods and supplier performance indicators are shown in Table 2.1.

Table 2.1: Selection methods with the consideration of indicators' weights

Researchers	Methods	Performance indicators/Applications
(Demirtas & Üstün, 2008)	ANP, Goal Programming	Quality (low defect rate, process capability); Service (on-time delivery, process flexibility, response to changes); Opportunities (consistency, mutual trust & ease of communication, support to design process); Cost (break in line, measurement & assessment cost); Risks (customer complaints, order delays, inability to meet further requirements)/ The plastic part of a refrigerator plant
Ng (2008)	Linear weighted programming	Supply variety, Quality, Distance, Delivery, Price/ Agricultural and construction equipment manufacturing.

Saen (2008)	Assurance Region of DEA model	Total cost of shipment, Price, Number of shipments per month, Number of bills received from supplier without errors, Number of on time shipments, Supply variety
Ting and Cho (2008)	AHP, Linear programming	Product price, Transportation costs, Ordering costs, Defect and scrap ratio, Product rejection ratio, Quality system, Delivery time-days, Delivery quantity shortage, Response to change, Lead time to order, Response to inquiry, Co-design production, Supply contracts, Assets and debts, Income and earnings, Cash flow/ Motherboard manufacturer
Ebrahim et al. (2009)	AHP, Linear programming, Scatter search algorithm	Length of guarantee period, Available services during guarantee period, Needed training for use of production(S), Length of the relation period, Importance of relations, Level of mutual satisfaction during relations, Technological level, Level of information technology, Capital of the supplier, Flexibility in manufacturing, Capability of getting in touch by buyer, Available information about supplier
Hsu and Hu (2009)	ANP	Procurement management (requirement of green purchasing, green materials coding and decoding, inventory of substitute material, supplier management); R&D management (capability of green design, inventory of hazardous substances, legal-compliance competency); Process management (management for hazardous substances, prevention of mixed material, process auditing, pre-shipment inspection, warehouse management); Incoming quality control (standard for incoming quality control, test equipment, record of incoming quality control); Management system (quality management system, environmental management system, hazardous substance management system, information systems)/Electronics company
Kokangul and Susuz (2009)	AHP, Integer Non-Linear Programming	Price performance (average time interval of price validity, price increasing trend, sending cost analysis, pay time, penalty for delayed payment, financial stability); Delivery performance (

		consistency in meeting delivery deadlines, order fill rate, flexibility in meeting customer needs, perfect delivery rate, labeling); Collaboration and developing performance (design capability, financial assets, communication openness, visits to supplier by management); Quality (the number of rejected items at entry level quality control, the number of rejected items at the process quality control, the number of rejected deliveries at the process quality control, the number of rejected items from warranty, the number of rejected safety items)
Wu et al. (2009)	ANP, Mixed Integer Programming	Management quality (supplier reputation, delivery performance, problem solving capabilities, long-term relationship potential); Technical quality (billing flexibility, production flexibility, product guarantee, performance monitoring capability); Operational quality (perfect order fulfillment, information system capability, interoperability with other parts, upgradability of hard and software); Fixed cost (capital investment, cost per unit, cost of network management system); Variable cost (appraisal cost, maintenance cost, cost of support services, failure product cost)
Saen (2010)	Assurance Region of DEA model	Total cost of shipment, Number of shipments per month, R&D cost, Number of bills without errors, Number of on time shipments
Lin et al.(2010)	Interpretive Structural Modeling (ISM), ANP	Delivery management capability (accuracy of delivered contents, on time delivery, delivery adjustment flexibility); Quality management capability (correctness of testing data, quality abnormal rate, capability to prevent repeated error, error judgment rate); Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform); Price (testing price, compensation rate for broken wafers, acceptance criteria)/ Semi-conductor industry
Kirytopoulos et	ANP, Multi-	Service (value added services- additional offers-, flexibility,

al. (2010)	Objective Mathematical Programming	problem solving, ease of communication); Supplier's profile(reputation, financial status, production facility and capacity, advertising); Quality (product specification, supplier's certification); Risk (production delays, delivery delays, low quality of delivered products, wrong quantity items); Other (relationships, preference)
Lin et al. (2010)	ANP, TOPSIS, Linear Programming	Price (material, assembly, transportation, management, negotiation); Quality (yield rate, reliability, innovation, repair ability, research and development); Service (attitude, communication, response speed, degree of communication, use of technology); Delivery (accuracy, lead time, location); Trust (credibility, capability)/ Motherboard manufacturer
Ordoobadi (2010)	AHP, Taguchi Methods	Benefits factors (flexibility, responsiveness to customers' needs, LR, reduction of capital investment, supplier's economies of skills and scale, supplier's competence, focus of internal resources on high value-added activities, supplier's empathy); Risk factors (LCQ of product/service, inability to meet fluctuations in demand, possibility of the suppliers becoming a competitor for the firm, negative impact on employees' moral, LSC, loss of cross-functional skills)
Zhu et al. (2010)	ANP, Portfolio analysis	Strategic performance measures (cost, quality, Time, flexibility, process management, Innovativeness); Organizational factors (culture, technology, relationship); Environmental factors (pollution controls, pollution prevention, environmental management system, resource consumption, pollution production)
(Z. H. Che, 2012)	Simulated Annealing Algorithm, Taguchi Method, AHP	Cost; Quality; Time/ Desktop computer mainframe company

Erdem and Gosen (2012)	AHP, Goal programming	Cost(unit purchase price, terms of payment, cost reduction projects); Quality(perfect order fulfillment, after sales service, application of quality standards, corrective & preventive action system, improvement efforts in tech & quality); Logistics(on time delivery, order lead time, delivery conditions & packaging standard, flexibility of transport, geographic distance); Technology(allocated capacity, flexibility of capacity, flexibility of technology, involvement in new product development)/ White goods manufacturer

Table 2.1 continued

Similar to previous works in this category (Ebrahim et al., 2009; Kokangul & Susuz, 2009; Ting & Cho, 2008), Erdem and Gocen (2012) implemented AHP model to evaluate the suppliers and based on these evaluations, a mathematical programming model was proposed for order allocation among suppliers. In this work, the two models were integrated into a decision support system to provide a dynamic, flexible and fast decision making environment (Erdem & Göçen, 2012).

Moreover, some researchers applied ANP to rate the suppliers and then exploited a mathematical programming method to assign order quantities (Aktar Demirtas & Ustun, 2009; Kirytopoulos et al., 2010; W. Y. Wu et al., 2009).

Liao and Kao (2010) employed Taguchi loss function to estimate the total loss of evaluation indicators in the supplier selection problem. The AHP was applied to assign the relative weight of each attribute. Furthermore a multi-choice goal programming model was constructed to let decision makers to have multi-aspiration levels for decision attribute in selecting the best supplier (Liao & Kao, 2010)

Lin et al. (2011) combined ANP and TOPSIS models to obtain the weights of suppliers. The final weight of each supplier was considered as a coefficient of objective function in the linear programming model to assign optimal order quantity to each supplier(C.-T. Lin et al., 2011).

Lin et al (2010) applied ISM approach to present the interrelation amongst the evaluation's dimensions and attributes in the supplier selection problem. Then ANP was employed to determine the weightings of each dimensions and attributes and finally, using the expectation index the suppliers were verified (Y. T. Lin et al., 2010).

Ordoobadi (2010) exploited Taguchi loss function to rank the suppliers. AHP method was utilized to calculate the relative importance of benefit and risk categories. While the composite loss score for each supplier was obtained by calculating the average of the weighted loss scores of two categories. Finally the supplier with the lowest composite loss score was chosen (Ordoobadi, 2010).

Che (2012) applied simulated annealing algorithm and Taguchi method to cluster the suppliers depending on the characteristics of customers' demands in the first phase. Then, AHP was implemented to weight every factor and considering the results of first phase, again, simulated annealing algorithm and Taguchi method were used to select the appropriate suppliers in the second phase (Z. H. Che, 2012).

2.1.2 Selection Methods under Fuzzy Environments

Ten out of ninety articles (11.11%) have been done under uncertain conditions and environments. In these articles, different methods were suggested to handle the existing uncertainty and vagueness in supplier selection process. The related information to these articles including the applied methods and performance indicators are shown in Table 2.2.

Table 2.2: Selection methods under Fuzzy Environments

Researchers	Methods	Performance Indicators/Applications
Carrera and Mayorga (2008)	Fuzzy inference system	Technological level; Economical situation; Production capacity; Market share; Quality level; Delivery rate; Cost reduction; Part quotation; Investment cost; Project time/pharmaceutical company
Li et al. (2008)	Rough set theory, Grey system theory	Product quality; Service; Delivery; Price
Ozgen et al. (2008)	AHP, Fuzzy theory, Possibilistic linear programming	Delivery performance; fill rate; perfect order fulfillment; order fulfillment lead-time; supply chain responsiveness; production flexibility; total logistics management costs; value added employee productivity; warrant costs; cash to cash cycle time; inventory days of supply; asset turns; environmental costs; green image; design for environmental; environmental management systems; environmental competencies/Pipe clamps and hanging systems manufacturer
Chen (2009)	Fuzzy set theory, Mathematical programming	Price; quality; delivery
Azadeh and Alem (2010)	DEA, Fuzzy DEA, Chance Constraint DEA	Cost; Delivery; Quality
Diaz-Madronero et al. (2010)	Fuzzy theory, Linear programming	Net cost, net rejections, net late deliveries
Kuo et al. (2010)	Particle Swarm Optimization (based on fuzzy neural network), ANN	Quality; Price; Location; Finance; Facility; Productivity; Long-term relationship capability; Technical capability; Managerial organization; Quick response for requirements/ Laptop company

Soner Kara (2011)	Fuzzy TOPSIS, Stochastic programming	Cost; References; Quality of product; Delivery time; Instituionality; Execution time/ Paper industry
Guneri et al. (2011)	Adaptive-Neuro Fuzzy Inference System	Quality, Cost; Delivery; Relationship closeness; Conflict resolution

Table 2.2 continued

Chen (2009) suggested a decision support model for supplier selection and order allocation problems. An interactive procedure based on past problem solving experiences was applied through a fuzzy-based mathematical programming approach to incorporate multiple uncertain criteria under the demand constraint of multiple items with varied importance to the purchasing firm (C. M. Chen, 2009).

Ozgen et al. (2008) used AHP to calculate the weights of the alternative suppliers for selecting the best ones. Then fuzzy theory was implemented to handle the imprecision data and consequently a multi-objective probabilistic linear programming approach was suggested to allocate order quantities to selected suppliers (Özgen, 2008).

Kuo et al. (2010) suggested a particle swarm optimization based fuzzy neural network for the supplier selection problem. The model derived the fuzzy relationship for qualitative attributes. Then quantitative data and fuzzy knowledge decision were integrated to get the best decision (Kuo, 2010).

Guneri et al. (2011) suggested an Adaptive Neuro-Fuzzy Inference System (ANFIS) for supplier selection problem. First, the factors were reduced by applying ANFIS input selection method. Then, the ANFIS structure was built using data related to selected attributes and the output of the problem (Güneri et al., 2011).

Soner Kara (2011) applied fuzzy TOPSIS method to rank suppliers in unknown environment. Furthermore a group of ranked suppliers were shifted in to a two-stage stochastic programming model to determine order quantities under demand uncertainty. (Soner Kara, 2011)

Except for Li's work which applied rough set theory to handle uncertainty, all other works implemented fuzzy set theory to cope with imprecise and vagueness in supplier evaluation and selection.

2.1.3 Selection Methods with the Consideration of Indicators' Weights under Fuzzy Environments

Forty-seven out of ninety articles (52.22%) considered the different weights for the supplier performance indicators under uncertain environments. The related information to these articles including the applied methods and indicators are shown in Table 2.3.

Table 2.3: Selection Methods with the consideration of Indicators' Weights under Fuzzy Environments

Researchers	Method	Performance Indicators/Applications
Chou and Chang (2008)	Fuzzy Simple Multi Attribute Rating Technique (SMART)	Cost (unit price, cost reduction plan); Quality (interval rejection rate, customer rejection rate); Delivery (lead time, flexibility); Organizational culture and strategy (management capability, strategic fit); Technical capacity (innovation, technical problem-solving)/ IT hardware manufacturing
Sevkli et al. (2008)	AHP, Fuzzy linear programming	Performance assessment (shipment, delivery, cost); human resource (number of employees, organizational structure, training, number of technical staff); quality system assessment (management commitment, inspection & control, quality planning, quality assurance); manufacturing (production capacity, maintenance, lead-time, up to date, storage, development); business criteria (reputation,

		location, price, patent, technical capability); information technology (RFID, DEI, internet)/TV set manufacturing company.
Yang et al. (2008)	Interpretive structural modeling, Fuzzy AHP, Sugeno's fuzzy integral	Quality (quality performance, quality containment and VDCS feedback); price &terms (price, terms, responsiveness, lead time, VMI/VOI hub Set Up cost); supply chain support (purchase order reactiveness, capacity support & flexibility, delivery/VMI operation) ; technology (technical support, design involvement, ECN/PCN process) / Electronic and IT industries
Amid et al. (2009)	Fuzzy weighted additive model, Fuzzy mixed integer linear programming	Quality; price; delivery
Amin and Razmi (2009)	Fuzzy set theory, QFD, A Weighted Linear Programming	Effective marketing & promotion; Experience; Financial strength; Management stability; Strategic alliances; Support resource; Monthly fee; Supply variety, Installation fee; Accessibility, reliability, security, and speed of supplier's services / Internet service providers
Boran et al. (2009)	Fuzzy weighting model, TOPSIS	Product quality; Relationship closeness; Delivery performance; Price
Guneri et al.(2009)	Fuzzy set theory, Linear programming	Relationship closeness; reputation and position in industry; performance history; conflict resolution; delivery capability/ Textile firm
Lee (2009)	Fuzzy AHP	Quality; flexibility; delivery; supplier's technology; joint growth; relationship building; cost of product; cost of relationship; supply constraint; buyer-supplier constraint; supplier's profile/ Thin film transistor liquid crystal display (TFT-LCD) suppliers
Lee et al. (2009)	Fuzzy AHP, Goal programming	Purchase cost; product yield rate; number of suppliers/ Notebook manufacturing company

Lin (2009)	Fuzzy preference programming, ANP, Multi-objective linear programming	Quality; Price; Delivery; Technique
Ming-Lang et al. (2009)	ANP, Choquet Integral (a non-additive fuzzy integral)	Customer focus (needs, complains, and expectations of customers); Competitive priority (price, innovation, launch new product, and quality performance); Strategic purchasing (purchasing function as a long-rang plan, purchasing involve risk and uncertainty, purchasing performance is measured); Top management support; Information technology/ Electronic industry
Ordoobadi (2009)	Fuzzy set theory	Delivery (compliance with due date, lead time, fill rate, flexibility); Service (reliability, empathy, responsiveness, assurance); Product (product rang, new product availability, recycled materials, ergonomic features); Quality (quality control rejection rate, customer rejection rate); Cost (purchase price, logistics)
Onut et al. (2009)	Fuzzy ANP, Fuzzy TOPSIS	Cost; References; Quality of product; Delivery time (days); Institutionality; Execution time (years)/ Telecommunication company
Wang and Yang (2009)	AHP, linear programming, Fuzzy compromise programming	Cost; key quality characteristics; processing flexibility; on-time delivery; response to change/ Lithium-ion battery protection IC industry
Wang et al. (2009)	Fuzzy AHP, TOPSIS	Cost; delivery; quality/ Pharmaceutical company
Zhang et al. (2009)	Vague Sets	Product quality; Service quality; Delivery time, Price
Amid et al. (2011)	Fuzzy linear programming, AHP	Product quality; Service quality; Delivery time, Price
Amin et al. (2010)	Fuzzy linear	unit cost; quality; percent of on time delivery; management

	programming	stability, mutual trust; strength of geographical location; international communication
Awasthi et al. (2010)	Fuzzy set theory, Fuzzy TOPSIS	Use of environment friendly technology; Environment friendly materials; Green market share; Partnership with green organizations; Management commitment; Adherence to environmental policies; Involvement in green projects; Staff training; Lean process planning; Design for environment; Environmental certification and pollution control initiatives
Aydin Keskin et al. (2010)	Fuzzy NNs (Adaptive Reassurance Theory)	Producing critical/safety; Producing similar part; Technical employee and equipment; Production capacity; Test capability; Managing diversification; Design and improvement; Financial; Price policy; Using certificates; Dispatch problems; Packing; transportation; Geographical location; Work safety; Environmental effects
Bai and Sarkis (2010)	Grey system, Rough set theory	Business and economic category: Cost (low initial price, compliance with cost analysis system, cost reduction activities, compliance with sect oral price behavior); Quality (conformance quality, consistent delivery, quality philosophy, prompt response); Time (delivery speed, product development type, partnership formation time); Flexibility (product volume changes, short set-up time, conflict resolution, service capability); Innovativeness (new launch of products, new use of technologies); Culture (feeling of trust, management attitude/outlook for the future, strategic fit, top management compatibility, compatibility among levels and functions, suppliers organizational structure and personnel); Technology (technological compatibility, assessment of future manufacturing capabilities, suppliers speed in development, suppliers design capability, technical capability, current

	manufacturing facilities and capabilities); Relationship (long-term relationship, relationship closeness, communication openness, reputation for integrity) Environmental category: Pollution controls (remediation, end-of-pipe controls); Pollution prevention(product adaption, process adaption); Environmental management system (establishment of environmental commitment and policy, identification of environmental aspects, planning of environmental objectives, assignment of environmental responsibility, checking and evaluation of environmental activities); Resource consumption (consumption of energy, consumption of raw material, consumption of water); Pollution production (production of polluting agents, production of toxic product, production of waste) Social category: Employment practices (disciplinary and security practices, employee contracts, equity labor sources, diversity, discrimination, flexible working arrangements, job opportunities, employment compensation, research and development, career development); Health and safety (health and safety incidents, health and safety practices); Local communities influence (health, education, housing, service infrastructure, mobility infrastructure, regulatory and public services, supporting educational institutions, sensory stimuli, security, cultural properties, economic welfare and growth, social cohesion, social pathologies, grants and donations, supporting community projects); Contractual stakeholders influence (procurement standard, partnership screens and standards, consumers education); Other stakeholders influence (decision influence potential, stakeholder empowerment, collective audience, selected audience, stakeholder engagement)

Buyukozkan and cifci (2011)	Fuzzy ANP	Organization, Financial performance, Service quality, Technology, Social responsibility & environmental competencies/ White goods industry
Chamodrakas et al.(2010)	Fuzzy preference programming, Rating scale AHP	Delivery (compliance with due date, compliance with quantity); cost; quality (remedy for quality problems, rejection rate from QC)/ Metal manufacturing company
Chen (2011)	DEA, Fuzzy weighting approach, TOPSIS	Quality; Cost; Delivery; Service; Technical and production capability, Relation combination; Organizational management/ Textile industry
Jolai et al. (2011)	Fuzzy AHP, Fuzzy TOPSIS, Goal programming	On time delivery; closeness of relationship with the supplier; supplier's product quality; supplier's technological capability; cost
Ku et al. (2010)	Fuzzy AHP, Fuzzy goal programming	Cost (product, freight cost, custom duties); quality (rejection, process capability, quality assessment); service (on time delivery, technical support, response to changes, ease of communication); risk (geographical location, political stability, economy) /Digital consumer products manufacturer
(Tseng & Chiu, 2013))	Fuzzy set theory, Grey rational analysis	Value-adding practices to a firm to ensure the profitability of suppler, Relationship, Delivery reliability, Quality, Satisfy customer needs, Flexibility, Service, Communication, Management, Green design, Environmental certificates, Green production plan, Cleaner production, Green purchasing, Life cycle assessment, Environmental management system, R& D capability, Innovation/ a printed circuit board manufacturer
Vinodh et al. (2011)	Fuzzy ANP	Business improvement (reputation of industry, financial strength, managing ability, organization customers); Extent of fitness (sharing of expertise, flexible practices, diversified customers); Quality (low defect rate, commitment to quality, improved process capability);

		Service (on time delivery, quick responsiveness ,supplier capacity); Risks (supply constraint, buyer supplier constraint, suppliers profile)/ Electronics switches manufacturing company
Kuo et al. (2010)	Artificial Neural Network (fuzzy neural network for qualitative data), ANP, DEA	Quality (reject rate, management commitment to quality, process improvement, warranties and claim policies, quality assurance); Cost (price performance value, compliance with sect oral cost behavior, transportation cost); Delivery (order fulfill rate, lead time, order frequency); Service (responsiveness, stock management, willingness, design capability); Environment (EUP, ODC, RoHS, ISO 14001, WEEE); Corporate social responsibility (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy)/Digital cameras manufacturer
Sanayei et al. (2010)	Fuzzy Theory, VIKOR	Product quality; On time delivery; Price/cost; Supplier's technological level; Flexibility
Wang (2010)	2-Tuple fuzzy linguistic computing	Product quality(product performance-reliability and accuracy-, level of technology); Delivery(condition of products on arrival, on-time delivery performance, accuracy in filling orders, order cycle time, ability to fill emergency orders, accuracy in billing and credit); Price/Cost (price of products and services, financial strength, cost harness capability); Service (post sales assistance and support, ability and willingness to assist with the design process, ease of communication)/ IC component company
Yucel and Guneri (2011)	Fuzzy set theory, Linear programming	Computing weights of factors in a way similar to TOPSIS approach
Dalalah et al. (2011)	Fuzzy theory, DEMATEL (decision making trial and	Unit price and payment, Delivery, Supplier factory capacity, Shipping method, Lead time, Location, Technical specifications, Certifications, Services and communications

	evaluation laboratory) model, TOPSIS	with the supplier, Compensation for waste, Printing complies to design and color, Easy open and spoon leveling, Available tests for packaging materials from supplier, Variation of dimensions, Stretch wrapping and clean separators and pallet size, Major customers with the same business, Certificate of supplier materials/Cans industry
Punniyamoorthy et al. (2011)	Structural Equation Modeling, Fuzzy AHP	Management and organization; quality; technical capability; production facilities and capabilities; financial position; delivery; services; relationships; safety and environmental concerns and cost/ Boiler manufacturer
Zeydan et al. (2011)	Fuzzy AHP, Fuzzy TOPSIS, DEA	New project management; Supplier management; Quality and environmental management; Production process management; Test and inspection management; Corrective & preventive actions management; Warranty cost ratio; Defect ratio; Quality management New project management; Supplier management; Quality and environmental management; Production process management; Test and inspection management; Corrective & preventive actions management; Warranty cost ratio; Defect ratio; Quality management
Amin and Zhang (2012)	Fuzzy set theory, Multi-objective programming, FAHP, Compromise programming	Supplier selection process in Closed-Loop Supply Chain (CLSC) network, Propose a framework for supplier selection criteria in Reverse Logistic (LR) based on supplier related, part related, and process related categories
Amindoust et. al (2012)	Fuzzy set theory, Fuzzy inference system	Profit, Quality, Delivery, Service, Environmental competencies, Environmental management system, The rights of stockholders, Work safety & Labor health
Baskaran et al. (2012)	Grey theory	Discrimination; Abuse of human right; Child labor; Long working hours; Unfair competition(society);

		pollution(environmental) / Textile and clothing industry
Buyukozkan and Cifci (2012)	Fuzzy ANP, Fuzzy Decision Making Trial and Evaluation Laboratory Model (DEMATEL), Fuzzy TOPSIS	Organization; Financial performance; Service quality; Technology; Green competencies
Chen and Chao (2012)	AHP, Consistent Fuzzy Preference Relation	Suppliers conditions (business relationships, financial situations, company's types, company organization); Price & Delivery (price, processing time of ordering, flexibility of order altering, delivery on time, manufacturing flexibility); Quality (product quality, product reliability, continuing improvement ability); Professional techniques (manufacturing facility and productivity, technique capability, design and development ability)/Electronic industry
Chu and Varma (2012)	Fuzzy set theory	Profit/sales; Financial stability; Capital and banking history; Discount; Delivery cost; Net price; Ordering cost; ISO 9001; Package; Customer rejecter; Warranty; Top management committee; Customer focus; Delivery lead time; Percentage of late delivery; Location; Quality problem; Urgent delivery; Honesty; ISO 14,000; Product range; Technical problem solving; Machinery; Infrastructure; Product line; Product variety; Length of inter-firm trust; Trust between key personnel
Ferreira and Borenstein (2012)	Fuzzy theory, Influence diagram	Economic (pressure over the food market, availability of raw-material, transportation costs, storage costs, structure of cooperatives, general demand, supplying costs); Social (financing availability, planted area, profitability); Technological (productivity, energy efficiency, crushing costs, producer knowledge, assistance knowledge)/

		Biodiesel plant
Golmohammadi and Mella-parast (2012)	Fuzzy set theory, Grey system theory	Price; Quality; Delivery; Transportation cost; Technology; Production system flexibility
Shaw et al.(2012)	Fuzzy AHP, Fuzzy Multi-objective Linear Programming	Cost; Quality rejection; Percentage of late delivered item; Greenhouse gas emission/Garment manufacturing company
Xiao et al. (2012)	Fuzzy Cognitive Map(FCM), Fuzzy soft set	Quality risk of the product (rejection rate of the product, on-time delivery rate, product qualification ratio, remedy for quality problem); Service risk (response to changes, technological and R&D support, ease of communication); Supplier's profile risk (financial status, customer base, performance history, production facility and capacity); Long-term cooperation risk (supplier's delivery ratio, management level, technological capability)
Yu et al.(2012)	Fuzzy AHP, Fuzzy multi-objective programming	Cost; Delivery; Quality/ Stereo manufacturer
Zuggari and Benyoucef (2012)	Fuzzy AHP, Knowledge simulation based on fuzzy TOPSIS model	Performance strategy (quality, pricing, age and position in the market, environmental engagement); Quality of service (delivery, service after sale, preventive actions, corrective actions); Innovation (research and development, service innovation); Risk (geographical location, political and economic stability)

Table 2.3 continued

Sevkli et al. (2008) integrated fuzzy linear programming model with AHP to address fuzziness issue and to take in to account of resource constraints in the supplier selection problem. The weights of the various criteria were calculated using AHP, were considered as the weights of the fuzzy multi-objective linear programming model (Sevkli et al., 2008).

Zhang et al. (2009) implemented vague sets group decisions. The model not only considered the relative importance of different decision-makers, but also included the accordance and difference in the decision group. To rank the suppliers, the judgments of all the decision-makers were integrated into a decision matrix (D. Zhang et al., 2009)

Amid et al. (2009) developed a fuzzy multi objective model to handle simultaneously the imprecision of data and determine the order quantities based on price breaks for each supplier. In this model, the weighted additive rule was applied to cope with the unequal importance of fuzzy goals and fuzzy constraints (A. Amid et al., 2009).

Ming-Lang et al. (2009) integrated ANP and Choquet integral to deal with the interdependency of factors, the nonlinear relationship among factors, and the environmental uncertainties in the supplier selection problem. The ANP was used simultaneously to consider the relationships of feedback and dependence of criteria. Choquet integral was applied to eliminate the interactivity of expert subjective judgment problems (Ming-Lang et al., 2009).

Guneri et al. (2009) proposed fuzzy linear programming model to solve multiple sourcing supplier selection problems. Linguistic variables were used to assess the importance weight of each criterion and the ratings of suppliers with respect to each criterion. The distances between alternative suppliers and fuzzy positive and negative ideal solutions were calculated to obtain closeness coefficients for using as coefficients of each supplier in linear programming model (Guneri et al., 2009).

Ordoobadi (2009) proposed a mathematical algorithm by applying fuzzy membership functions to rank the suppliers (Ordoobadi, 2009).

Wang and Yang (2009) applied a multi objective linear programming model for allocating order quantities to each supplier in quantity discount environments. In this model, AHP was applied to calculate the weights of the objective functions for each criterion. Then the multi-objective model was reformulated into a fuzzy compromise programming approach to have a more reasonable compromise solution (T. Y. Wang & Yang, 2009).

Zhang et al. (2009) applied vague set theory to cope with uncertain information in supplier selection. First, linguistic variables were used to assess the rating of factors. Second, degree of similarity and probability of vague sets were used to determine the ranking order of suppliers (D. Zhang et al., 2009).

Bai and Sarkis utilized grey system and rough set theory to introduce additional levels of analysis and application of Li et al.'s methodology(G. D. Li et al., 2008) for supplier selection problem (Bai & Sarkis, 2010).

Amid et al. (2011) developed a weighted max–min fuzzy multi-objective model to complete the Amid et al.'s work in 2009 for supplier selection and order allocation problems. The current model considered imprecision of data and varying importance of quantitative/qualitative attributes. AHP was used to determine the weights of attributes in the model (A Amid et al., 2011).

Amin et al. (2011) suggested a strategic model for supplier selection which included two stages. In the first stage, fuzzy logic was integrated with quantified SWOT algorithm. In the second stage, the output of SWOT algorithm was implemented as an input in a fuzzy linear programming model to determine the order quantity (Saman Hassanzadeh Amin et al., 2011) .

Yucel and Guneri (2011) proposed a weighted additive fuzzy programming approach for supplier selection and order allocation problems. The weights of attributes were obtained by applying a procedure to calculate fuzzy positive ideal rating and fuzzy negative ideal rating for applying in a fuzzy multi-objective linear model (Yucel & Guneri, 2011).

Yang et al. (2008) employed ISM approach to clarify the relationships among the sub-criteria in the vendor selection problem. The fuzzy AHP method was used to compute the relative weights for each criterion. Also, the non-additive fuzzy integral was applied to obtain the fuzzy synthetic performance of each criterion. Finally, the best vendor was determined according to the overall aggregating score of each vendor using the fuzzy weights with fuzzy synthetic utilities (J. L. Yang et al., 2008).

Lee (2009) applied a fuzzy AHP model with the consideration of opportunities and risk besides benefits and costs for buyers to select the best suppliers (A.H.I. Lee, 2009).

Again, Lee et al. (2009) operated fuzzy AHP to analyze the importance weights of multiple attributes in the supplier selection problem. These weights were used as the coefficient of goals in the goal programming model (Lee et al., 2009).

Wang et al. (2009) developed fuzzy hierarchical TOPSIS method to simplify the complicated metric distance method which had been applied by Chen et al. (2005) and to rectify Chen's fuzzy TOPSIS idea (2000) in the supplier selection problem. In the modified model, fuzzy AHP was used to calculate the fuzzy weight of each attribute. Also, the weights were inserted to TOPSIS method for ranking suppliers (J. W. Wang et al., 2009).

Chamodrakas et al. (2010) suggested an approach to modify Mikhailov's fuzzy preference programming method (2004) (Mikhailov, 2004) according to Liberatore's rating scale AHP method (1995) (Liberatore & Stylianou, 1995) for the supplier selection problem in an electronic marketplace environment. A Simon's satisfying model was used for supplier pre-qualification and the modified rating-scale AHP version fuzzy preference programming method was applied for final supplier evaluation (Chamodrakas et al., 2010).

Ku et al. (2010) utilized fuzzy goal programming considering the manufacturer's supply chain strategies for the supplier selection problem. Fuzzy AHP was applied to calculate the relative weights of attributes and then the weight numbers were used as goals' coefficients in objective function of fuzzy goal programming to determine the optimal order allocation (Ku et al., 2010).

Jolai et al. (2011) employed fuzzy AHP to calculate the importance weights of attributes and a modified fuzzy TOPSIS approach to gain the scores of alternative suppliers in multi-product environment. Also, the goal programming method was applied to construct a multi-objective mixed integer linear programming model to determine the quantity of order allocation to each selected supplier in each period (Jolai et al., 2011).

Punniyamoorthy et al. (2011) employed SEM approach to obtain the relative weights of the quantitative and qualitative indicators in the supplier selection problem. Fuzzy AHP was used to gain the relative weights of suppliers to achieve supplier selection score (Punniyamoorthy et al., 2011).

Zeydan et al. (2011) applied fuzzy AHP model to find indicators weights and also fuzzy TOPSIS model to rank the suppliers. In this model, qualitative variables were transformed into a quantitative variable for using in DEA approach as an output to determine the efficient and inefficient suppliers (Zeydan et al., 2011).

Boran et al. (2009) applied fuzzy set theory to determine the importance weights of attributes and the ratings of suppliers versus the attributes. The related fuzzy numbers were passed to TOPSIS model for ranking suppliers (Boran et al., 2009).

Awasthi et al. (2010) applied fuzzy TOPSIS method to generate an overall performance score for each supplier in supply chain. The sensitivity analysis was performed to present the impact of attributes weights on decision making process (Awasthi et al., 2010).

Tseng and Chiu (2013) proposed a grey relational analysis for supplier selection problem. To determine the importance weights of attributes and alternatives, fuzzy set theory was applied (Tseng & Chiu, 2013).

Chen (2010) suggested DEA approach to screen efficient and inefficient suppliers. Then, using fuzzy set theory the efficient suppliers were ranked through TOPSIS model (Y. J. Chen, 2011).

Dalalah et al. (2011) modified DEMATEL approach which determined the cause and effect relationship between attributes to handle fuzzy concept in the supplier selection problem. The results of modified DEMATEL model were shifted to modified TOPSIS model to find the best supplier (Dalalah et al., 2011).

Lin (2009) integrated the Fuzzy preference programming method with ANP to measure the weights of the suppliers. Then, the weights were used as coefficients in the objective function of the multi-objective linear programming model to obtain optimal allocation of orders (R. H. Lin, 2009).

Onut et al. (2009) applied fuzzy ANP to calculate indicators weights in the supplier selection problem. Then these weights were shifted to the fuzzy TOPSIS methodology to rank the suppliers (Önüt et al., 2009).

Buyukozkan and Cifci (2011) utilized fuzzy ANP model in sustainable supplier selection problem. In this model, the fuzzy linguistic terms were used to analyze attributes and missing values were estimated through incomplete preference relations (Buyukozkan & Çifçi, 2011).

Vindoh et al. (2010) implemented fuzzy ANP approach to find the most appropriate supplier. A sensitivity analysis was performed on varying the relative importance of different attributes (Vinodh et al., 2011).

Aydin Keskin et al. (2010) presented Fuzzy Adaptive Resonance Theory Neural Networks for supplier evaluation and selection. In this model, the most appropriate supplier(s) were selected and clustered (AydIn Keskin et al., 2010).

Kuo et al. (2010) implemented ANN approach to predict the performance measure value of each supplier and used ANP model to determine the attributes weights. Then, they combined ANN and ANP with DEA to select the best suppliers (Kuo et al., 2010).

Chou and Chang (2008) proposed fuzzy set theory into a simple multi-attribute rating technique (SMART) to select the appropriate supplier. A sensitivity analysis was carried out to present the effect of variance in the risk coefficients in ranking order of suppliers (Chou & Chang, 2008).

Amin and Razmi (2009) operated quality function deployment (QFD) to determine the best suppliers based on qualitative attributes. Also, a weighted linear programming model was adopted to consider quantitative metrics as a quantitative model. Finally these two models were composed and selected the best suppliers (S.H. Amin & Razmi, 2009).

Sanayei et al. (2010) developed multi-criteria optimization and compromise solution approach (the Serbian name is VIKOR) for ranking suppliers. A hierarchy MCDM model based on fuzzy sets theory and VIKOR method was introduced to determine the closeness to the ideal solution. Also, the differences between this method and TOPSIS model were referred in the article (Sanayei et al., 2010).

Wang (2010) proposed a fuzzy linguistic multi-agent model to cope with heterogeneous information and to prevent information loss problems in the supplier evaluation issue. The model was based on 2-tuple fuzzy linguistic information which composed of a linguistic term and a number (W. P. Wang, 2010).

Amin and Zhang (2012) employed fuzzy set theory to rank suppliers based on qualitative attributes through a weighting procedure. Then, a multi-objective mixed integer linear programming model was applied to rank the suppliers based on quantitative attributes and also to assign order allocation to selected suppliers. It is noted that, the fuzzy AHP method was combined with compromise programming to determine the weights of each objective function in the proposed model (Saman Hassanzadeh Amin & Zhang, 2012).

Buyukozkan and Cifci (2012) integrated fuzzy ANP and fuzzy DEMATEL to obtain the attributes weights in green supplier selection issue. The results of the integration were passed to fuzzy TOPSIS to rank the suppliers (Büyüközkan & Çifçi, 2012).

Baskaran et al. (2012) applied grey approach for supplier selection in uncertain and inconsistent environment. The attributes weights were considered as linguistic variables based on grey numbers (Baskaran et al., 2012).

Chu and Varma (2012) suggested a multiple levels multiple criteria decision making model under fuzzy environment to evaluate and select the suppliers. The importance weights of attributes and the ratings of suppliers versus qualitative attributes were assessed in linguistic values. Using Center of area method, all of the related fuzzy numbers were ranked before their weighted ratings aggregation. Finally, an additive weighted rating from the last to the first level in the attributes structure was applied to evaluate the suppliers (T.-C. Chu & Varma, 2012).

Xiao et al. (2012) applied fuzzy cognitive map to obtain the weights of attributes using a practical swarm optimization algorithm. Then, a fuzzy soft set was implemented to select the suppliers (Xiao et al., 2012).

Yu et al. (2012) developed a multi-objective mathematical model for supplier selection under lean procurement. Also, fuzzy AHP was applied to calculate the decision preferences for the objective functions and constraints in the mathematical model. The results of the model have shown that decision makers prefer vendors who can promise tighter delivery schedules rather than on cost and quality (Yu et al., 2012).

Zouggari and Benyoucef (2012) used fuzzy AHP model for supplier selection. Unlike other related order allocation papers which applied mathematical programming for order allocation issue, they applied a knowledge simulation based on fuzzy TOPSIS model in order allocation problem (Zouggari & Benyoucef, 2012).

Ferreira and Borenstein (2012) integrated influence diagram and fuzzy concept for supplier selection issue, emphasizing the dynamics characteristics of a long-term relationship with suppliers (Ferreira & Borenstein, 2012).

Chen and Chao (2012) used the structure of attributes in AHP model and proposed a procedure using consistent fuzzy preference relations to build the decision matrices to rank the suppliers (Y.-H. Chen & Chao, 2012).

Shaw et al. (2012) implemented fuzzy AHP to weight the attributes. These weights were passed to fuzzy multi-objective linear programming to select the suppliers and assign orders allocation (Shaw et al., 2012).

In more than half papers of this category (twenty-four out of forty-seven) AHP or ANP integrated methods have been applied.

2.1.4 Selection Methods with no Consideration of Indicators' Weights under Certainty

Sixteen out of ninety (17.78%) papers solved the supplier selection problem under certain conditions with the same importance-degree for the indicators. The related information to these articles including the applied methods and indicators are shown in Table 2.4.

Table 2.4: Selection Methods with no consideration of Indicators' Weights under Certainty

Researchers	Methods	Performance Indicators/Applications
(Z. Che & Wang, 2008)	Mathematical Programming, GA	Cost; On time delivery; Quality
Ha and Krishnan (2008)	AHP, DEA, ANN	Production facilities; Quality management intention; Quality system outcome; Claims; Quality improvement; Response to claims; Delivery; Organizational control; Business plans; Customer communication; Internal audit; Data administration
Sanayei et al. (2008)	Multi-Attribute Utility Theory (MAUT), Linear Programming	Reliability (damage free orders, on time orders); Responsiveness (lead time, return product velocity); Flexibility (order increase/decrease flexibility, revise flexibility); Cost/Financial (total cost, payment terms); Infrastructure (quality system certification, company size, reputation)
Sadeghi moghadam et al. (2008)	Fuzzy inference system (FIS), ANN,GA	Purchase cost; Transaction cost; Holding cost /Sewing machine industry
Basnet and Weintraub (2009)	Mixed Integer Programming, GA	Cost; Quality; Delivery
kheljani et al. (2009)	Mixed- integer nonlinear programming	Price, fixed/order cost, production rate, setup cost, production variable cost
Li and Zabinsky (2011)	Mixed integer programming	Quality, delivery, cost(transaction and inventory)
Luo et al. (2009)	Artificial neural network (radial basis function)	Management and technology ability (R&D investments, environment adaption ability, product response time, compatible corporation culture), financial quality, company resources (human resource, reputation, IT level, value of trademark) ,quality (cost of quality, product quality, service) /Electrical appliance and equipment manufacturing

Wu (2009)	DEA, ANN, Decision Tree	Quality management practices and systems; Documentation and self-audit; Process/manufacturing capability; Management of the firm; Design and development capabilities; Cost reduction capability; price; delivery; Economic environmental; Location
Chang and Hung (2010)	Rough Set Theory	Quality; Price; Delivery performance; Service; Flexibility
Osman and Demirli (2010)	Goal Programming, Benders Decomposition Technique	On time delivery; Cost; To meet the expected demand increase/ Aerospace company
Sawik (2010)	Mixed integer programming	Under discount environment Cost; Quality; Delivery
Zhang and Zhang (2011)	Mixed Integer Programming, Branch and Bound Algorithm	Quality; Service; Delivery; Maintenance; Cost
Aksoy and Ozturk (2011)	ANN	Quality; JIT delivery performance; Location; Price
Mafakheri et al. (2011)	AHP, Dynamic Programming Approach	Price performance (average time interval of price validity, price increasing trend, sending cost analysis, pay time, penalty for delayed payment, financial stability); Delivery performance (consistency in meeting delivery deadlines, order fill rate, flexibility in meeting customer needs, perfect delivery rate, labeling); Environmental performance (similar to Humphreys et al. (2003)); Quality (the number of rejected items at entry level quality control, the number of rejected deliveries at entry level quality control, the number of rejected items at the process quality control, the number of rejected deliveries at the process quality control, the number of rejected items from warranty, the

		number of rejected safety items)
Yeh and Chuang (2011)	Multi-objective optimization modeling, Genetic algorithm	Production cost, Production time, Transportation cost, Transportation time, Average product quality, Green principles (green image, product recycling, green design, green supply chain management, pollution treatment cost, environment performance assessment)/ Electronic industry

Table 2.4 continued

Ha and Krishnan (2008) applied AHP to assign weight to the qualitative attributes in single sourcing and multiple sourcing of supplier selection process. Then, the remained quantitative attributes along with the scores for each supplier obtained by AHP were shifted to DEA and ANN to calculate the performance efficiency of each supplier. Both results were compiled into one efficiency index using a simple averaging method. Also a cluster analysis was performed for suppliers (Ha & Krishnan, 2008).

Kheljani et al. (2009) formulated a mixed-integer nonlinear programming model in supplier selection process. The objective function of the model is minimization of the total cost of the supply chain that included both the buyer's cost and suppliers' cost. Demand rate for the buyers and production rate for the suppliers were considered as constraints (Gheidar Kheljani et al., 2009).

Wu (2009) suggested a classification model and a regression model for the supplier selection problem. First DEA was utilized to classify suppliers into efficient and inefficient clusters. Then firm performance-related data was used to train decision tree or neural networks model and to apply the trained models to new suppliers (D. Wu, 2009).

Li and Zabinsky (2011) suggested a two-stage stochastic programming model and a chance-constrained programming model to identify the best suppliers and to assign order quantities in business volume-discount environments. Both models were formulated on a mixed integer program. The uncertainties for demand and supplier capacity were considered with a probability distribution in the models (L. Li & Zabinsky, 2011).

Sawik (2010) presented mixed integer programming models for single or multi-objective supplier selection cases in non-discount or discount environment to determine the optimal allocation of orders for the approved suppliers. Risk constraints associated with uncertain quality and reliability of supplies, were considered in this model (Sawik, 2010).

Sadeghi Moghadam et al. (2008) applied fuzzy neural network to control the inventory and select the optimal supplier. The results of the model were passed to a mixed integer programming and because of the complexity and non-linear nature of the model, a genetic algorithm was used to solve it (Sadeghi Moghadam et al., 2008).

Luo et al. (2009) developed a quantitative model of classifying suppliers into one of the four various types of the Kraljic's classification matrices (1983). The model was based on radial basis function artificial neural network to reduce the information-processing time and to achieve a robust and speedy solution (Luo et al., 2009).

Basnet and Weintraub (2009) constructed a mixed integer programming model for the supplier selection problem. A GA approach was applied to determine the efficient supplier for large-sized problems in the model (Basnet & Weintraub, 2009).

Osman and Demirli (2010) developed a bilinear goal programming model to handle the supplier selection problem. A modified Benders decomposition method was applied to decompose the model in to a binary supplier selection model and a mixed integer distribution planning model(Osman & Demirli, 2010).

Chang and Hung (2010) adopted rough set theory to analyze the rules of supplier selection derived from a set of samples to classify the suppliers (B. Chang & Hung, 2010).

Che and Wang (2008) developed an optimal mathematical model for multiple products in the supplier selection problem due to common and non-common parts. The model was constructed to allocate suitable order quantities to selected suppliers under the limitation of production capacity. A GA approach was applied to find acceptable results for the model (Z. Che & Wang, 2008).

Aksoy and Ozturk (2011) applied ANN technique to select suppliers and to evaluate the selected suppliers' performance in just-in-time production environments. The suppliers were classified through this model (Aksoy & Öztürk, 2011).

Sanayei et al. (2008) applied multi-attribute utility theory to rate the suppliers while considering uncertainty. The obtained rates were then utilized as coefficients for the objective function of the linear programming model to identify the optimal quantities of order allocation (Sanayei et al., 2008).

Zhang and Zhang (2011) structured a mixed integer programming model for the supplier selection problem. A branch and bound algorithm was applied to solve the model and to obtain the exact optimal solution (J. Zhang & Zhang, 2011).

Mafakheri et al. (2011) used AHP model to select the appropraite suppliers. Then, a bi-objective mathematical model was structured to assign orders allocation and a dynamic programming approach was devised to solve the model (Mafakheri et al., 2011).

Yeh and Chuang (2011) integrated multi-objective optimization model with genetic algorithm for green supplier selection. They found the set of Pareto-optimal solutions to rank the suppliers (Yeh & Chuang, 2011).

2.2 Critical discussions and Research Directions

In this work, 90 journal papers, which have been published in the period from 2008 to 2012, dealing with supplier selection problem applying an extensive range of methods and performance indicators were gathered. Some observations based on these papers are mentioned and some comments are made in the following subsections.

2.2.1 Critical discussions on Performance Indicators

Among the extensive range of performance indicators, the most popular ones are scanned and summarized considering avoidance of their duplications. It is noteworthy having a look at the four aforementioned Tables; for each indicator different definitions have been found in the articles as shown in Table 2.5, Table 2.6, and Table 2.7.

Table 2.5: The most popular economic supplier selection indicators

	Supplier 's Performance indicator	Different definitions of indictor	Researchers/the number of applications of indicators
Economic	Quality	Inspection & control, Reliability of product performance, Quality system assessment, Defect and scrap ratio, Low defect rate, Customer rejection rate, Internal rejection rate, Customer rejection rate, Yield rate, Quality system certifications, return product velocity, Test capability	All references except for Gheidar Kheljani et al. (2009), Baskaran et al. (2012) /**88**
	Cost/price	Unit price, Cost reduction plan, Transportation costs, Ordering costs, Storage costs, Warrant costs, Maintenance costs, Failure product cost	All references except for Boran et al. (2009), Awasthi et al. (2010), Baskaran et al. (2012)/**87**
	Delivery	Lead time , Order fulfill rate, Condition of products on arrival, Compliance with due date and quantity, Accuracy In filling orders, Accuracy in billing and credit, Labeling, Consistency in	All references except for Boran et al. (2009), Awasthi et al. (2010), Baskaran et al. (2012), Lee (2009)/**86**

	meeting delivery deadlines, JIT delivery performance, Lead time	

From Table 2.5, it can be seen that the “Quality”, “Cost/price”, and “Delivery” are the most popular economic criteria. Also, “Flexibility”, “Technology capability”, “Service”, “Financial capability”, and “Organization & control” are the secondary popular economic criteria, respectively as shown in Table 2.6.

Table 2.6: The more popular economic supplier selection indicators.

	Supplier ‘s Performance indicator	Different definitions of indictor	Researchers/the number of applications of indicators
Economic	Technology capability	Innovation, Technical problem-solving, Technical employee and equipment, Allocated capacity, involvement in new product development, Productivity, Produce knowledge, Assistance knowledge, Current manufacturing facilities	Chou and Chang (2008); Sevkli et al. (2008); Yang et. al (2008);Wang (2010); Chen & Chao, (2012); Luo et al. (2009);Ku, et al., (2010); Kuo, (2010); (Tseng & Chiu, 2013)); Aydin Keskin et al. (2010); Sanayei et al. (2010);Buyukozkan and Cifci (2012); Carrera and Mayorga (2008); Buyukozkan and cifci (2011); Chen (2011); Dalalah et al. (2011); Punniyamoorthy et al. (2011); Erdem and Gosen (2012); Ferreira and Borenstein (2012); Ebrahim, et al., (2009);Ordoobadi, (2009); Bai & Sarkis, 2010;Zhu, Dou, & Sarkis, (2010)/**23**
	Financial capability	Assets and debts, Income and earnings, Cash flow, Capital investment	Vindoh et al. (2010); Wang (2010); Luo et al. (2009); Kuo, (2010); Sanayei, et. al,(2008); Kokangul and Susuz (2009); Aydin Keskin et al. (2010); Carrera and Mayorga (2008); Buyukozkan and cifci (2011); Punniyamoorthy et al. (2011); Ferreira and Borenstein (2012); Ordoobadi, (2009); Kirytopoulos et al. (2010); Liao and Kao (2010);

			Ordoobadi, (2010)/**15**
	Flexibility	Response to change, Product volume changes, Short set-up time, Conflict resolution	Chou and Chang (2008); Ting & Cho,(2008) ; Lee (2009); H. Chen & Chao, (2012) ; Yang et. al (2008); Wang & Yang, (2009); Kuo, (2010): Lin, et al., (2010); Tseng & Chiu, (2013); Sanayei, et. al ,(2008); Kokangul and Susuz (2009); Sanayei et al. (2010); Demirtas & Üstün, (2008), Ozgen et al. (2008), Guneri et al.(2009); Erdem and Gosen (2012);Ebrahim, et al., (2009); Ordoobadi, (2009); Bai & Sarkis, (2010); Chang and Hung (2010); Kirytopoulos et al. (2010);Ordoobadi ,(2010);Zhu, Dou, & Sarkis,(2010)/**23**
	Organization & control	Top management support, Organization management, Inventory level reduction, Lot size reduction, Reduction in plant stoppage due to shortage of material, Outlook for future, Compatibility among levels and functions	Vindoh et al. (2010); Sevkli et al. (2008);Chou and Chang (2008); Chen & Chao, (2012), Kuo,(2010); Buyukozkan and cifci (2011); Chen (2011);Punniyamoorthy et al. (2011); Ha & Krishnan, (2008), Bai & Sarkis,(2010);Zhu, Dou, & Sarkis, (2010)/**12**
	Service	Ease of communication, Response time for customers' request, Efficiency of engineering support, Fulfilling customers' special request, Customer information service platform, Length of guarantee period, Empathy	Vindoh et al. (2010); Wang (2010); Luo et al. (2009); Ku, et al., 2010); Kuo, et al., (2010); Lin et al. (2010); (Tseng & Chiu, 2013)); Demirtas & Üstün, (2008); Buyukozkan and cifci (2011);Chen,(2011);Punniyamoorthy et al., (2011);Ha & Krishnan,(2008), Li, et al., (2008); Zhang et al. (2009); Bai & Sarkis, (2010); Chang and Hung (2010); Kirytopoulos et al. (2010); Liao and Kao (2010); Zhang and Zhang (2011)/**19**

Table 2.6 continued

Finally, the more popular environmental and social criteria are shown in Table 2.7.

Table 2.7: The more popular environmental and social supplier selection indicators

	Supplier 's Performance indicator	Different definitions of indictor	Researchers/the number of applications of indicators
Environmental	Environmental competencies	Inventory of hazardous substance, Green design, Green production plan, Cleaner production, Safety and environmental concerns, Adherence to environmental policies, Green purchasing, Life cycle assessment, , Green supply chain management, Product recycling, Environmental effects, Pollution, Greenhouse gas emission, Recycled material, Use of environmental technology & materials, Green market share, Partnership with green organizations, Involvement in green projects, Resource consumption	Hsu and Hu (2009); AydIn Keskin, et al., (2010); Buyukozkan and Cifci (2012); Buyukozkan and Cifci (2011); Ozgen et al. (2008); Baskaran et al. (2012); Shaw et al.(2012); Awasthi et al. (2010); Bai & Sarkis, (2010); Zhu, Dou, & Sarkis, (2010); Punniyamoorthy et al. (2011); Yeh and Chuang (2011)/**12**
	Environmental management system	Environmental certificates, EUP, ODC, ROHS, ISO 14001, WEEE	Hsu and Hu (2009); Kuo, et al.,(2010); Ozgen et al. (2008); Awasthi et al. (2010); Bai & Sarkis, (2010); Zhu, Dou, & Sarkis, (2010); Yeh and Chuang (2011)/**7**
Social	Social-responsibilities	The interests and rights of employee, The rights of stakeholder, Information disclosure, Respect for the policy, Discrimination, Abuse of human right, Unfair competition, Trust, Employment practices, Local	Kuo, et al.,(2010); Buyukozkan and Cifci (2011); Baskaran et al. (2012); Bai & Sarkis, (2010)/**4**

		communities influence	
	Work safety & labor health	Long working hours, Child labor	Kuo, et al.,(2010); AydIn Keskin, et al., (2010); Bai & Sarkis, (2010)/**4**

From a sustainable point of view, threefold merits including economic, environmental, and social have been seen for indicators in some papers. But, the majority of the papers considered only economic merits, and in a few of them environmental and social merits –separately or together- were considered including economic merits. So, these indicators are combined into three categories (economic, environmental, and social) to propose a comprehensive framework for sustainable supplier selection indicators as shown in Figure 2.1.

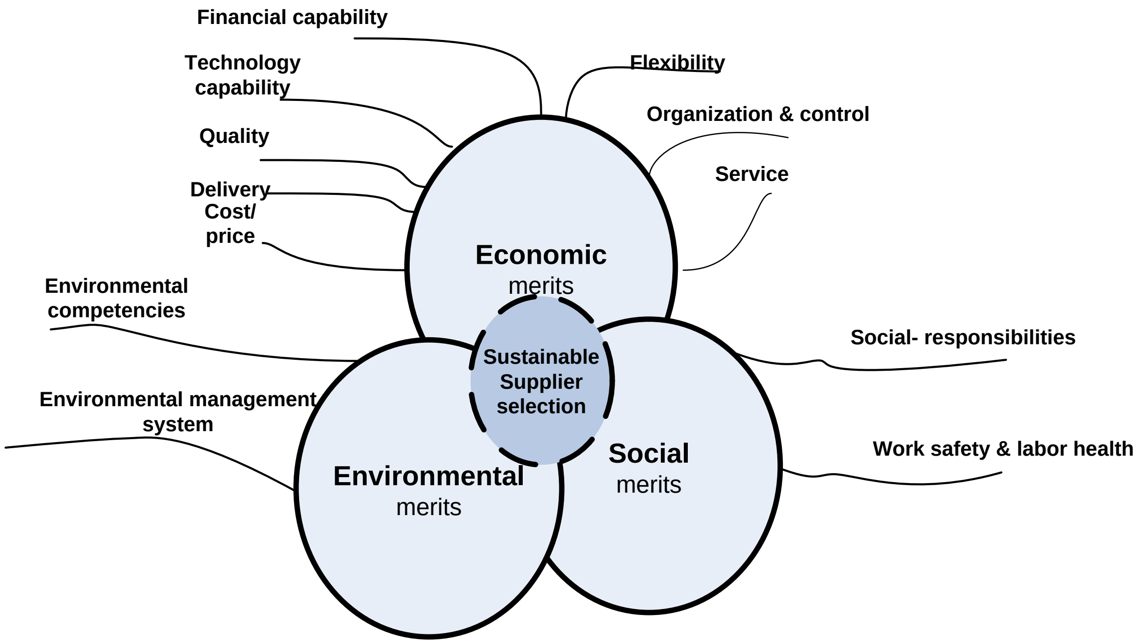


Figure 2.1: Sustainable supplier selection indicators' framework.

2.2.2 Critical Discussions on Supplier Selection Methods

Among the four aforementioned categories for supplier selection methods, the third one which considered both aspects- the relative importance of performance indicators and fuzzy environments - has received the most attentions. Having a look at Table 2.1, Table 2.2, Table 2.3, and Table 2.4, it is obvious that the majority of recent publications (in 2012) have fallen to this category and this shows the importance of the two mentioned aspects in supplier selection problem. The most popular approaches in this category are AHP integrated methods. The majority of these methods combined fuzzy set theory and AHP to handle the uncertainties. The wide applicability of the AHP approach is due to its simplicity, ease of use, and great flexibility (William Ho, 2008). But, AHP can compare a very limited number of suppliers, usually not more than 15 (Y.-M. Wang et al., 2008). In addition, if there are more than seven factors at the same level in hierarchy construction, there would be too many pair wise comparisons, and it is tough for decision makers to make a choice (Saaty, 1990). This issue has been taken in to account in the AHP-based supplier selection papers in aforementioned Tables and none of the papers considered more than seven criteria in each level. In fact in the AHP approach, the pair wise comparison procedure must be employed in a total of $n \times (n-1)/2$ comparisons needs to be answered in a group of n indicators. When the number n of indicators in a group increases, the required number of pair wise comparisons also increase. As a result of too many questions and comparisons, it is easy to causes evaluator’s mental confusion, and thus easily results in inconsistent situations (Y.-H. Chen & Chao, 2012). There are several suggestions to overcome the shortcoming of AHP in supplier selection papers. For example, Lee et al. (2009) proposed Delphi method to reduce the number of criteria and sub-criteria while keeping real important ones. Also the Fuzzy extended AHP (D. Y. Chang, 1996) Was suggested for relatively easier, less time taking and less computational expense than other fuzzy AHP methods in their paper (Amy H. I. Lee, 2009). Chamodrakas et al. (2010) applied Liberatore’s rating scale method (Liberatore, 1987) to cope with the explosion in the number of pair wise comparisons when the number of suppliers and/or the number of performance indicators is large (Chamodrakas et al., 2010). Amin & Zhang (2012) applied integrated AHP method in the supplier selection problem. However, they did not use the AHP to weight the suppliers in the first because; in their model the suppliers were assessed based on different parts and therefore, a lot of pair wise comparisons must have been performed. So, they proposed a ranking method based on fuzzy set theory to handle this issue (Saman Hassanzadeh Amin & Zhang, 2012). Chen & Chao (2012) used consistent fuzzy preference relations (CFPR) (Herrera-Viedma et al., 2004) to establish decision matrices. Using CFPR, only $(n-1)$ comparison is required to be evaluated and consistency is guaranteed for a group of n-criterion. The rest of $(n-1)\times(n-2)/2$ comparisons were computed by using additive transitivity in the procedure of CFPR. The human comparisons are reduced and hence human errors can be reduced (Y.-H. Chen & Chao, 2012). So, working on methods which cope with the large number of indicators and alternatives with consideration of the two aspects of third category (Selection Methods with the consideration of Indicators' Weights under Fuzzy Environments), it would be a useful dimension in research. Moreover, focusing on other basic methods in supplier selection problem considering these two aspects can be strengthening the supplier selection literature. DEA is one of the basic methods and is the most used standalone technique in supplier selection (Falagario et al., 2012; W. Ho et al., 2010).However, verifying the applied methods in the third category, it is obvious that DEA has not received enough attention. So, centralizing on DEA model in consideration of the two mentioned aspects can pave a way to future research.

2.3 Background of the Data Envelopment Analysis Approach

Efficiency measurement has been a subject of tremendous interest as organizations have struggled to improve productivity. Reasons for this focus were best stated by Farrell (1957) in his classic paper on the measurement of productive efficiency. ‘‘The problem of measuring the productive efficiency of an industry is important to both the economic theorist and the economic policy maker. If the theoretical arguments as to the relative efficiency of different economic systems are to be subjected to empirical testing, it is essential to be able to make some actual measurements of efficiency. Equally, if economic planning is to concern itself with particular industries, it is important to know how far a given industry can be expected to increase its output by simply increasing its efficiency, without absorbing further resources.” Farrell further stated that the primary reason that all attempts to solve the problem had failed, was due to a failure to combine the measurements of the multiple inputs into any satisfactory measure of efficiency. These inadequate approaches included forming an average productivity for a single input (ignoring all other inputs), and constructing an index of efficiency in which a weighted average of inputs is compared with output. Responding to these inadequacies of separate indices of labor productivity, capital productivity, etc., Farrell proposed an activity analysis approach that could more adequately deal with the problem. His measures were intended to be applicable to any productive organization; in other words, ‘‘from a workshop to a whole economy.” Unfortunately, he confined his numerical examples and discussion to single output situations, although he was able to formulate a multiple output case. After Farrell’s seminal work, and building on those ideas, Charnes et al. (1978), responding to the need for satisfactory procedures to assess the relative efficiencies of multi-input multi-output production units, introduced a powerful methodology which has subsequently been titled data envelopment analysis (DEA). The original idea behind DEA was to provide a methodology whereby, within a set of comparable decision making units (DMUs), those exhibiting best practice could be identified, and would form an efficient frontier (Cook & Seiford, 2009).

To date, DEA has been adopted as the most comprehensive tool for measuring efficiency and productivity of decision making units and many successful applications are reported using DEA in various subjects such as the efficiency measurement of hospitals (Baskaran et al., 2012), manufacturing efficiency (Korpela et al., 2007; Liu & Wang, 2008; Talluri et al., 2006; H. H. Yang, 2010). Also, many publications have implemented DEA approach for supplier selection issue. Braglia and Petroni (2000) employed DEA to select the best suppliers in bottling industry. To prevent choosing "false positive" supplier, both cross-efficiency and Maverick index were considered in their work (Braglia & Petroni, 2000). Liu et al. (2008) proposed a DEA model to measure the efficiency of suppliers in agricultural equipment manufacturing (Liu & Wang, 2008). Forker and Mendez (1997) implemented DEA for supplier selection in electronic industry (Forker, 1997). Similar to Braglia and Petroni (2000), the cross-efficiencies were measured to find the appropriate suppliers (Ferreira & Borenstein, 2012).

Narasimhan et al. (2001) employed DEA model to evaluate and classify alternative suppliers in the telecommunications industry (Narasimhan et al., 2001). Talluri and Narasimhan (2004) proposed DEA using cross-efficiencies and statistical methods to classify the suppliers in telecommunications industry (Talluri & Narasimhan, 2004). Garfamy (2006) implemented DEA to evaluate the suppliers based on total cost of ownership concept (Garfamy, 2006). Ross et al. (2006) applied DEA in communications industry for supplier selection problem (Ross et al., 2006). Saen (2006) improved a DEA model to measure the efficiencies of technology suppliers in nuclear power industry (Reza Farzipoor Saen, 2006). Seydel (2006) applied DEA to handle the supplier selection problem without any inputs in consumer product manufacturing (Seydel, 2006).

Talluri et al. (2006) proposed a so-called chance-constrained DEA model to measure the efficiencies of suppliers in the presence of stochastic performance measures in pharmaceutical industry .(Talluri et al., 2006). Wu et al. (2007) applied an augmented imprecise DEA for supplier selection in electronic industry to cope with imprecise data (T. Wu et al., 2007). Saen (2008, 2010) utilized the assurance region of DEA model for supplier selection as mentioned in section 2.3.1 (R.F. Saen, 2008a, 2010). Azadeh and Alem (2010) applied DEA, fuzzy DEA, and chance-constrained DEA models to tackle with certainty, uncertainty, and probability in supplier selection as seen in section 2.3.2 (Azadeh & Alem, 2010). Chen (2011) and Zeydan (2011) proposed integrated DEA models for supplier selection as mentioned in section 2.3.3 (Y. J. Chen, 2011; Zeydan et al., 2011). Also, Ha and Krishnan (2008) and Wu (2009) suggested integrated DEA models for supplier selection problem as mentioned in section 2.3.4 (Ha & Krishnan, 2008; D. S. Wu, 2009).

2.4 Summarized Research Directions

From the above literature review, the following conclusions or directions can be drawn.

i. It is pellucid that very little supplier selection research has been conducted in the turf of considering sustainability issues. The effects of incorporation of environmental and social aspects including economic aspects in determining the supplier performance indicators for the selection process remain in the fissure and hence needed research attention.

ii. Two aspects have been received more attentions in supplier selection literature. Firstly, the relative importance issue of the performance indicators. Secondly, supplier selection decision under fuzzy data. Hence, this thesis attempts to make a bridge between these two aspects through a new method to extend the supplier selection literature.

iii. Previously most of the supplier selection DEA-based methods hardly considered the two aforesaid aspects in their process. It is due to the shortcomings of DEA which lead to completely ignore these two aspects in the earlier researches. Therefore, development of DEA approach for supplier selection problem is in the virgin area of research and in the field of knowledge.

iv. Expanding the number of performance indicators and also the amount of suppliers complicate the selection process. So, further research is necessary for coming up with open ended method to adapt any number of supplier selection criteria and candidate suppliers for today's manufacturing including small, medium and large enterprises.

2.5 Theoretical Background on Selection Methods

This section briefly reviews the basic theoretical background on the related theories in the proposed supplier selection model including fuzzy set theory, fuzzy inference system, and DEA, respectively.

2.5.1 Fuzzy Set Theory

Zadeh (1965) introduced fuzzy set theory to cope with the imprecision and uncertainty which is inherent to the human judgments in decision making processes through the use of linguistic terms and degrees of membership. A fuzzy set is a class of objects with grades of membership. A normalized membership function is between zero and one (Zadeh, 1965). These grades present the degree of stability with which special element belongs to a fuzzy set. To express fuzzy sets on the mathematical point of view, consider a set of objects X . The set is explained as follows:

$$X = x_1, x_2, \ldots\ldots\ldots, x_n \tag{2.1}$$

where, x_i is an element in the set X .

A membership value (μ) expresses the grade of membership related to each element x_i in a fuzzy set A , which shows a combination as below:

$$A = \mu_1(x_1), \mu_2(x_{2)}, \ldots\ldots\ldots, \mu_n(x_n) \tag{2.2}$$

In this research, fuzzy set theory is applied to consider the decision makers' preferences in relation to performance indicators to calculate the weights of them and also in relation to the suppliers' performance with respect to these indicators. Some related descriptions of fuzzy theory are used that include membership functions of the linguistic variables, fuzzy operators, and defuzzification as follows.

2.5.1.1 Fuzzy Membership Functions of the Linguistic Variables

In the fuzzy set theory, as the degree to which an element belongs to a certain set increases its membership function grade approaches 1, otherwise it approaches 0. Therefore, the concept of characteristic function from general set can be extended in to the concept of membership function for the fuzzy set (Y. J. Chen, 2011). Several functional forms of the membership function are available to represent different situations of fuzziness; for example, linear shape, concave shape and exponential shape. Two commonly used membership function types are linear triangular and linear trapezoidal membership functions(Y. J. Chen, 2011). In this research, the triangular membership function is utilized because of linear interpolation between fuzzy set elements. Triangular membership function also gives reasonably good performance in terms of theoretical calculations as compared to other shapes. A triangular fuzzy number can be shown as $\tilde{w} = (a^l, a^m, a^u,)$ where, a^l, a^m, and a^u are the lower , medium ,and upper amount of fuzzy number, respectively in Figure 2.2 . The triangular membership function is also defined in equation (2.3).

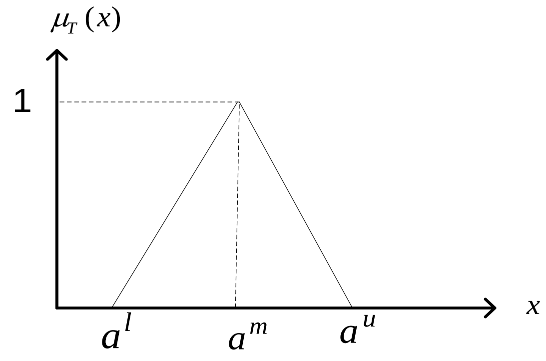


Figure 2.2: Triangular membership function.

$$\mu_{\tilde{w}}(x) = \begin{cases} 0 & if \quad x < a^l \\ \frac{1}{a^m - a^l}(x - a^l) & if \quad a^l \le x \le a^m \\ \frac{1}{a^m - a^u}(x - a^u) & if \quad a^m \le x \le a^u \\ 0 & if \quad x > a^u \end{cases} \tag{2.3}$$

2.5.1.2 Fuzzy Operators

According to the definition of fuzzy numbers, suppose that $\tilde{X}$ and $\tilde{Y}$ are two triangular fuzzy numbers as

$$\tilde{X} = (x^l, x^m, x^u) \tag{2.4}$$

$$\tilde{Y} = (y^l, y^m, y^u) \tag{2.5}$$

The basic fuzzy operators are shown as below.

$$\tilde{X} + \tilde{Y} = (x^i + y^i, x^m + y^m, x^u + y^u) \tag{2.6}$$

$$\tilde{X} - \tilde{Y} = (x^i - y^i, x^m - y^m, x^u - y^u) \tag{2.7}$$

$$\tilde{X} * \tilde{Y} = (x^i * y^i, x^m * y^m, x^u * y^u) \tag{2.8}$$

$$\tilde{X} / \tilde{Y} = (x^i / y^i, x^m / y^m, x^u / y^u) \tag{2.9}$$

2.5.1.3 Defuzzification

Fuzzy number is converted to crisp number through the defuzification action. Popular defuzzication approaches are included the center of area method (COA), bisector of area method (BOA), mean of maximum method (MOM), smallest of maximum method (SOM), and the largest of maximum method (LOM) (Sivanandam et al., 2007). Among deffuzzification methods, the COA method which is the most popular method(Ordoobadi, 2009) is applied in this thesis as shown in (2.10).

$$x_{COA} = \frac{\sum_{i=1}^{n} x_i . \mu_i (x_i)}{\sum_{i=1}^{n} \mu_i (x_i)} \tag{2.10}$$

where, x_i is an element in the set X as mentioned in (2.1) and (2.2) and x_{COA} is the deffuzzified output.

2.5.2 Fuzzy Inference System

Fuzzy inference is the process of formulating the mapping from given input(s) to an output using fuzzy logic, the mapping then provides a basis from which a decision can be made. The most common approaches to FIS are Sugeno and Mamdani approaches. Sugeno approach would be difficult to give a linguistic interpretation of the information that is described in the rule base. While, Mamdani approach is typically used in modeling human expert knowledge (Al-Najjar & Alsyouf, 2003). Mamdani in

1974, investigated the feasibility of using compositional rule of inference (Mamdani, 1974).The Mamdani FIS system has 4 parts as shown in Figure 2.3.

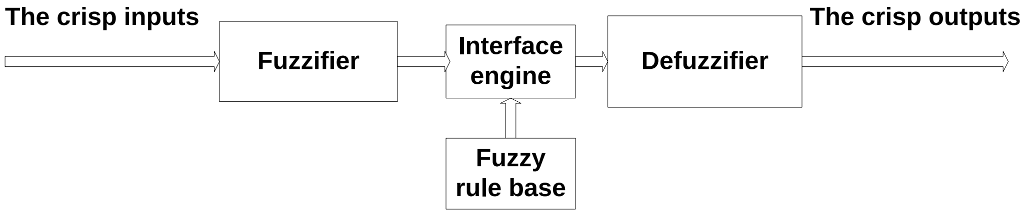


Figure 2.3: The Mamdani's fuzzy inference system.

- Fuzzifier: the fuzzy sets of inputs are represented by membership functions to transfer crisp inputs into fuzzy inputs.
- Fuzzy rules: the main part of the FIS model is "Rules". The fuzzy "if-then" rules are defined on the basis of experts' knowledge in each area. A fuzzy rule can be written as "if x_1 is a_1 and x_2 is b_1 , then y is c_1" so that x_1 and x_2 are variables, y is a solution variable, and a_1, b_1 , and c_1 are fuzzy linguistic terms.
- Interface engine: the fuzzy interface engine takes integrations of the identified fuzzy sets considering the fuzzy rule and allocates to integrate the related fuzzy area individually.
- Defuzzifier: transforms the fuzzy output to crisp output. Among 4 parts of FIS, defuzzification process has the most computational complexity. The defuzzifier finally identifies a numerical output value.

2.5.3 DEA Approach

DEA is a mathematical programming method which was proposed by Charnes et al (1978) to evaluate the relative efficiency of decision making units (DMUs) by multiple inputs and outputs but with no obvious production function to aggregate the data in its entirety. Relative efficiency is defined as the ratio of total weighted output to total weighted input. By comparing p units with J outputs denoted by y_{js} (the amount of output j provided by unit s), $j = 1,2,....,J$, and l inputs denoted by x_{ls}, $l = 1,2,....,L$ (The amount of input l provided by unit s) the efficiency measure for sth unit ($s = 1,2,....,p$) is obtained as below.

$$h_s = \underset{u_j, v_l}{Max} \frac{\sum_{j=1}^{J} u_j y_{js}}{\sum_{l=1}^{L} v_l x_{ls}} \tag{2.11}$$

The variables u_j and v_l are the weights of outputs and inputs, respectively which are non-negative and obtained by the model.

A second set of constraints requires that the same weights, when applied to all DMUs, do not provide any unit with the efficiency greater than one. This condition appears in the following set of constraints:

$$\frac{\sum_{j=1}^{J} u_j y_{j\lambda}}{\sum_{l=1}^{L} v_l x_{l\lambda}} \leq 1 \qquad , \lambda = 1,2,....,p \tag{2.12}$$

The efficiency ratio ranges from zero to one, with DMU s being considered relatively efficient if it receives a score of one. Thus, each unit will choose weights so as to maximize self-efficiency, given the constraints.

The result of the DEA is the determination of the hyper planes that defines an envelope surface or Pareto frontier. DMUs that lie on the surface determine the envelope and are deemed efficient, whilst those that do not are deemed inefficient (Adler et al., 2002).

The formulation described above can be translated into a linear program, which can be solved relatively easily and a complete DEA solves S linear programs, one for each DMU. The linear programming of DEA formulation done by Charns et.al assumes that the production function exhibits constant returns-to-scale, often referred to as the

CCR model, is implemented in this thesis. The CCR model measures the efficiency of s th supplier z_s to a set of peer suppliers in the model below:

$$
\begin{aligned}
& MaxZ_s = \sum_{j=1}^{J} u_j y_{js} \\
& st: \\
& \sum_{l=1}^{L} v_l x_{ls} = 1 \\
& \sum_{j=1}^{J} u_j y_{j\lambda} - \sum_{l=1}^{L} v_l x_{l\lambda} \leq 0 \qquad \lambda = 1,2,\ldots,p \\
& u_j, v_l \geq \varepsilon \quad l = 1,2,\ldots,L; \quad j = 1,2,\ldots,J
\end{aligned} \tag{2.13}
$$

The symbol ε is non-Archimedean constant to assure that all weights are non-negative. For s th unit if the objective value is 1, it is said efficient; otherwise, it is inefficient.

2.5.3.1 Supper Efficiency Model of DEA Approach

One of the important problems in the DEA literature is that of ranking those DMUs deemed efficient by the DEA model, all of which have a score of unity. Andersen and Petersen (1993), proposed the super efficiency model to solve the ranking problem (Anderson et al., 2003). The methodology enables an extreme efficient unit s to achieve an efficiency score greater than one by removing the s th constraint in the DEA formulation, as shown in model.

$$
\begin{aligned}
& MaxZ_s = \sum_{J=1}^{J} u_J y_{Js} \\
& st: \\
& \sum_{l=1}^{L} v_l x_{ls} = 1 \\
& \sum_{j=1}^{J} u_j y_{j\lambda} - \sum_{l=1}^{L} v_l x_{l\lambda} \leq 0 \qquad \lambda = 1,2,\ldots,p, \qquad \lambda \neq s \\
& u_j, v_l \geq \varepsilon \quad l = 1,2,\ldots,L; \quad j = 1,2,\ldots,J
\end{aligned} \tag{2.14}
$$

In fact, the super-efficiency model involves executing the standard DEA model but under the assumption that the DMU being evaluated is excluded from the reference set.

2.5.3.2 Assurance Region Model of DEA Approach

One serious drawback of DEA applications in supplier selection has been the absence of decision maker judgment, allowing total freedom when allocating weights to input and output data of supplier under analysis. This allows suppliers to achieve artificially high efficiency scores by indulging in inappropriate input and output weights. The most widespread method for considering judgments in DEA models is, perhaps, the weight restrictions inclusion. Weight restrictions are allowed to integrate the managerial preferences in terms of relative importance levels of various inputs and outputs. The idea of conditioning the DEA calculations to consider the presence of additional information arose first in the context of bounds on factor weights in DEA's multiplier side problem (R.F. Saen, 2010). This led to the development of assurance region models by Thompson et al. (1990) (Thompson et al., 1990). Assurance region model of DEA (DEA/AR) technique links either only input weights or only output weights as seen in equation (2.15).

$$I_L \le \frac{v_l}{v_{l+1}} \le I_{u,} \quad , \quad O_L \le \frac{u_J}{u_{J+1}} \le O_u \tag{2.15}$$

where, I_L and I_u are the lower and upper bounds, respectively, on the ratio $\frac{v_l}{v_{l+1}}$. Also, O_L and O_u are the lower and upper bounds, respectively, on the ratio $\frac{u_J}{u_{J+1}}$.

These constants reflect the importance of input and output variables based on the decision makers' preferences. The mentioned restrictions are added to the DEA in respect of all the DMUs being compared.

CHAPTER 3

RESEARCH METHODOLOGY

In this chapter, the research methodology and its relevant subjects that were used in developing the integrated FIS-DEA method in order to overcome the shortcomings of DEA technique are described for sustainable supplier selection problem. This chapter presents the research design and methodology in a brief manner. The extended research design and detailed methodology are given in Chapter 4.The proposed method is tested by implementing of two test beds. The sources of theoretical information and methods of data collection are included in this chapter. The error measurement criteria are defined in the last section to use for the validation of the proposed FIS-DEA method.

3.1 Methodology of the Research

This research was done based on the two important aspects which were found from the literature review involved in supplier selection problem “which supplier performance indicators to be considered from sustainable point of view” and “what methods to be applied for selection of such suppliers”. These aspects are taken into account in supplier selection to establish a useful decision model for manufacturing companies. So, the relevant suppliers’ performance indicators and supplier selection methods in manufacturing were derived through extensive literature review to find research gaps. Based on the literature review shown in Chapter 2, a conceptual supplier selection model is figured out and shown in Chapter 4. The various stages of this research are shown in Figure 3.1.

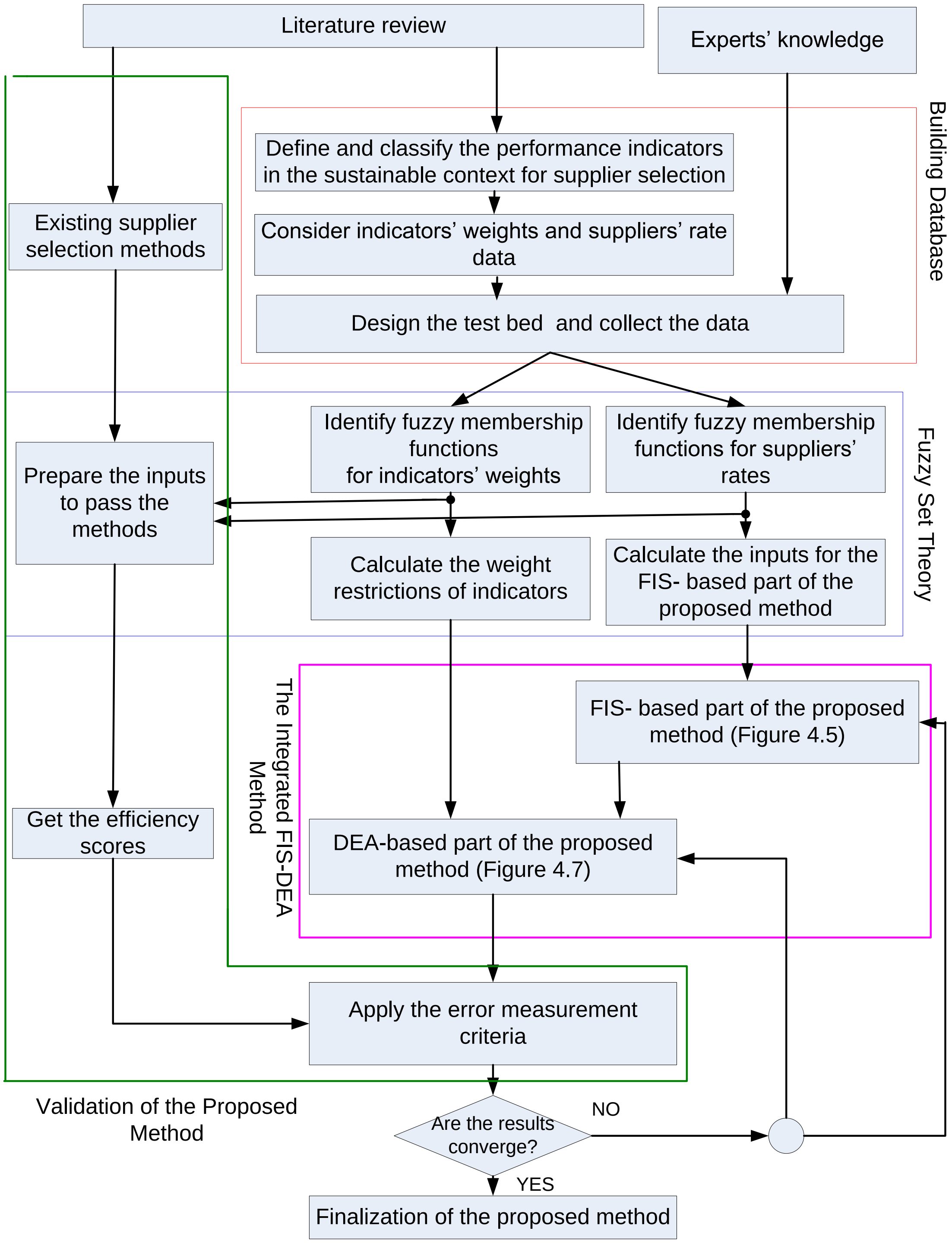


Figure 3.1 : The methodological flow of the research.

The contents of the figure are self-explanatory. However, first, the database was built based on extensive literature review and experts' knowledge. Obviously, for sustainable supplier selection a large number of performance indicators or criteria setting had a paramount importance. For these indicators, the relevant data are normally used in linguistic forms. As these data were opinion-based data and not the measurement data, it was necessary to pass them through the fuzzy filter to get the useful fuzzy numbers for further analysis. The appropriate fuzzy theories were applied to get fuzzy membership functions. The mentioned numbers as inputs were applied in the proposed integrated FIS-DEA method to get the ranking results. To show the validation of the proposed method, an existing FIS-based supplier selection method was implemented and its ranking results were compared with the results of the proposed FIS-DEA method by applying errors measurement criteria.

The detailed explanation on sustainable supplier selection criteria, methods to be considered, mathematics to be utilized and the results expected are placed in Chapter 4.

In the above flowchart, the highlighted three phases and the FIS-based supplier selection method are described in detail in Chapter 4. As seen in Figure 3.1, building data base phase is done based on the literature review and the experts' knowledge through the data collection which are described below.

3.2 Sources of Theoretical Information

For a review required to locate the further research needs, authentic sources of knowledge was considered inevitable. Today, the Internet is a great source of information collection of theoretical material. Search engines like ISI Web of Knowledge, Science direct, Emerald, Springer, and Google were utilized to download authentic papers for reliable information for this research. A comprehensive reference of the academic literature on supplier evaluation and selection was obtained. The papers which have been published in peer-reviewed/archival journals, proceedings or edited books were collected. The literature search was conducted based on the key words “supplier selection”, or “vendor selection” and “sustainability”. First the full text of each article was read to separate the articles that were not related to sustainability, supplier evaluation methods and evaluation criteria for supplier selection. Conference papers, master’s and doctoral dissertations, textbooks and unpublished working papers were not included. However, it was possible that some of the published papers were missing from the list. Finally about 100 papers were used from 22 journals. These papers are then rigorously scanned for supplier selection criteria and methods. The literature review (Chapter 2) has shown the contents relevant to the topic of the research and the rationale of this work.

3.3 Data Collection Process

To execute the proposed FIS-DEA method that would fit the sustainable supplier selection criteria and to recognize its priorities for supplier selection problem, the suppliers’ related data had to be collected. So, the appropriate questioners were prepared and designed based on the performance indicators which were derived from the sustainable supplier selection indicators’ framework vividly explained in Chapter 2. Since the proposed method is supported from two aspects (the relative importance of performance indicators and the suppliers’ performance with respect to these indicators), two forms of questionnaires were designed based on the two aforesaid aspects (See Appendix-A). The online questionnaire and in person/telephone interviews were made for data collection for this research. The questionnaires were passed into the procurement team of two companies in two countries, namely Iran and Malaysia, to collect the data. The useful information to execute the proposed method including the performance indicators’ weights and the suppliers’ performance with respect to these indicators were gained for two companies. Also, some questions in case of the supplier ranking results on the basis of their own ranking system were asked from the procurement teams through interviews. In fact, the usefulness of the proposed FIS-DEA may be shown through comparing the suppliers' ranking results of the proposed FIS-DEA method with the results of the ranking system being used in these companies. But, both of the companies declared that their supplier selection process was more cost oriented and only some limited economic criteria have taken into account in practice. A simple diagram of their selection process has been figured out in Appendix-D. However, they adhered to the importance of sustainability issues and may be considered these scenarios in present day requirement and in future. Since the proposed heuristic FIS-DEA method is open-ended in case of the number of performance indicators and the number of candidate suppliers, the existing related data (for cost and some other limited economic criteria) of the selection process in two companies was not enough to execute the proposed method. So, test beds which are able to replicable testing of scientific theories and they have used as computational tools (Karapetyan & Gutin, 2010) are used to deal with testing the applicability of the proposed FIS-DEA method which have been described in Chapter 5.

3.4 Design of the Test Bed

A test bed is a platform for experimentation of large development projects. Test beds allow for rigorous, transparent, and replicable testing of scientific theories, computational tools, and new technologies. In fact, verification, validation, and testing of heuristic methods can be done by utilizing a test bed. It is obvious that, the test-bed on which the new and heuristic methods are tested has a key role in the comparison of new and developed methods (Silberholz & Golden, 2010). Silberholz & Golden (2010) studied how to create and classify instances in a new test-bed and how to make sure other researchers have access to the problems for future meta-heuristic comparisons.

To dates, test beds have been used in different area of decision making such as selection of trading agents in electronic auction markets (Rodriguez-Aguilar et al., 1998) , improving public participation in environmental decision making (Willis et al., 2004), transportation corridor decision making (Zietsman et al., 2006), and decision on the optimization of production assembly line sequencing (Tahriri, 2012). So, the test bed scenario can be used in supplier selection as a central decision making in SCM.

Two types of classification using test-beds are as follows (Silberholz & Golden, 2010):

- Using the existing test-beds
- Developing new test-beds

Existing test-beds are used when comparing a new heuristic method to an existing one. Then, the results will be comparable, allowing relative gap calculations between the two methods.

Often, new test beds were developed when an existing test-bed was found insufficient (due to being too small to effectively test a proposed method). So, a new test bed need to be developed. Two points must be addressed when developing any new test-beds: the goals in creating the test-beds and accessibility of new test instances (Silberholz & Golden, 2010). The goals of a problem suite include mimicking the real-world problem instances while providing test cases that are of various types and difficulty levels. When creating a new test-bed, the focus should be on providing others with the access to the problem instances. This will allow other researchers to make comparisons more easily, while ensuring the problem instances are widely used (Tahriri, 2012).

To execute the proposed method, the existing test beds in supplier selection were found not sufficient in case of sustainability issues and the number of performance indicators. Thus, the new test bed must be designed to implement the proposed method and this is done in section 5.1.1

3.5 Error Measurement Criteria

In statistics, the mean squared error (MSE) of an estimator is one of many ways to quantify the difference between values implied by an estimator and the true values of the quantity being estimated. MSE is a risk function, corresponding to the expected value of the squared error loss or quadratic loss. MSE measures the average of the squares of the "errors." The error is the amount by which the value implied by the estimator differs from the quantity to be estimated. The difference occurs because of randomness or because the estimator doesn't account for information that could produce a more accurate estimate (Lehmann & Casella, 1998). The MSE is the second moment (about the origin) of the error, and thus incorporates both the variance of the estimator and its bias. For an unbiased estimator, the MSE is the variance of the estimator. Like the variance, MSE has the same units of measurement as the square of the quantity being estimated. In an analogy to standard deviation, taking the square root of MSE yields the root mean square error (RMSE), which has the same units as the quantity being estimated; for an unbiased estimator, the RMSE is the square root of the variance, known as the standard deviation. Values of MSE may be used for comparative purposes. Two or more statistical models may be compared using their MSEs as a measure of how well they explain a given set of observations: The unbiased model with the smallest MSE is generally interpreted as best explaining the variability in the observations and is called the best unbiased estimator or MVUE (Minimum Variance Unbiased Estimator). Both linear regression techniques such as analysis of variance estimate the MSE as part of the analysis and use the estimated MSE to determine the statistical significance of the factors or predictors under study. The goal of experimental design is to construct experiments in such a way that when the observations are analyzed, the MSE is close to zero relative to the magnitude of at least one of the estimated treatment effects. MSE is also used in several stepwise regression techniques as part of the determination as to how many predictors from a candidate set to include in a model for a given set of observations. Minimizing MSE is a key criterion in selecting estimators. Among unbiased estimators, minimizing the MSE is equivalent to minimizing the variance, and the estimator that does this is the minimum variance unbiased estimator. However, a biased estimator may have lower MSE.

Squared error loss is one of the most widely used loss functions in statistics, though its widespread use stems more from mathematical convenience than considerations of actual loss in applications. Carl Friedrich Gauss, who introduced the use of mean squared error, was aware of its arbitrariness and was in agreement with objections to it on these grounds (Lehmann & Casella, 1998). The mathematical benefits of mean squared error are particularly evident in its use at analyzing the performance of linear regression, as it allows one to partition the variation in a dataset into variation explained by the model and variation explained by randomness. The use of mean squared error without question has been criticized by the decision theorist James Berger. Mean squared error is the negative of the expected value of one specific utility function, the quadratic utility function, which may not be the appropriate utility function to use under a given set of circumstances. There are, however, some scenarios where mean squared error can serve as a good approximation to a loss function occurring naturally in an application (Berger, 1985). Like variance, mean squared error has the disadvantage of heavily weighting outliers (Bermejo & Cabestany, 2001). This is a result of the squaring of each term, which effectively weights large errors more heavily than small ones. This property, undesirable in many applications, has led researchers to use alternatives such as the mean absolute error, or those based on the median.

In statistical modeling the MSE, representing the difference between the actual observations and the observation values predicted by the model, is used to determine the extent to which the model fits the data and whether the removal or some explanatory variables, simplifying the model, is possible without significantly harming the model's predictive ability.

According to the mentioned criteria, a method by minimum value of MSE, RMSE, and, MAE has the best performance in comparison with the other method.

In this research, the aforesaid error measurement criteria were employed to verify, assess the capability, and efficiency of the proposed FIS-DEA method.

The proposed FIS-DEA method was evaluated and its performance was calculated by the mean-squared error (MSE), Root MSE (RMSE) and Mean Absolute Error (MAE) as compared to the FIS-based supplier selection method. The relevant mathematics is shown in equations (3.1), (3.2), and (3. 3).

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(A_i - F_i)^2 \tag{3.1}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(A_i - F_i)^2} \tag{3.2}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|(A_i - F_i)\right| \tag{3.3}$$

in the above equations, A_i and F_i are the experimental value and the predicted value, respectively and n is the total number of data where $i = 1,2,....,n$.

CHAPTER 4

CONCEPTUAL SUPPLIER SELECTION MODEL AND ANALYTICAL METHOD

This Chapter presents a new conceptual decision model for sustainable supplier selection under uncertain environments on the basis of integration of FIS and DEA theories. Based on the literature review, the research gaps were found that need to be extended the existing supplier selection models. An integrated FIS-DEA method is proposed for supplier selection and it is explained step by step in this chapter. The process of application of the existing FIS-based supplier selection method in literature is explained in order to compare and show the validation of the proposed FIS-DEA method is also included in this chapter.

4.1 Conceptual Supplier Selection Model

Going through literature, it is found that there are two important questions which involved in supplier selection problem including “which supplier performance indicators” and “which supplier selection methods” would be considered in the selection process. So, the existing suppliers’ performance indicators and supplier selection methods in manufacturing are derived through extensive literature review to find research gaps.

Focusing on the research gaps, the conceptual model for supplier selection has been proposed. The term conceptual model is used to refer to a model which is formed after understanding/learning the pros-and-cons related to the field in focus through an extensive literature review from the authentic sources and developing a mind-map considering the relevant issues and aspects. Conceptual models represent human intentions or semantics. Conceptualization from observation of physical existence and conceptual modeling are the necessary means that human being employ to think and solve problems. Concepts are used to convey semantics during various natural languages based communication. Since a concept might map to multiple semantics by itself, an explicit formalization is usually required for identifying and locating the intended semantic from several candidates to avoid misunderstandings and confusions in conceptual models (Yucong & Cruz, 2011).

These research gaps lead to propose a new decision model for sustainable supplier selection which its flowchart is shown in Figure 4.1.

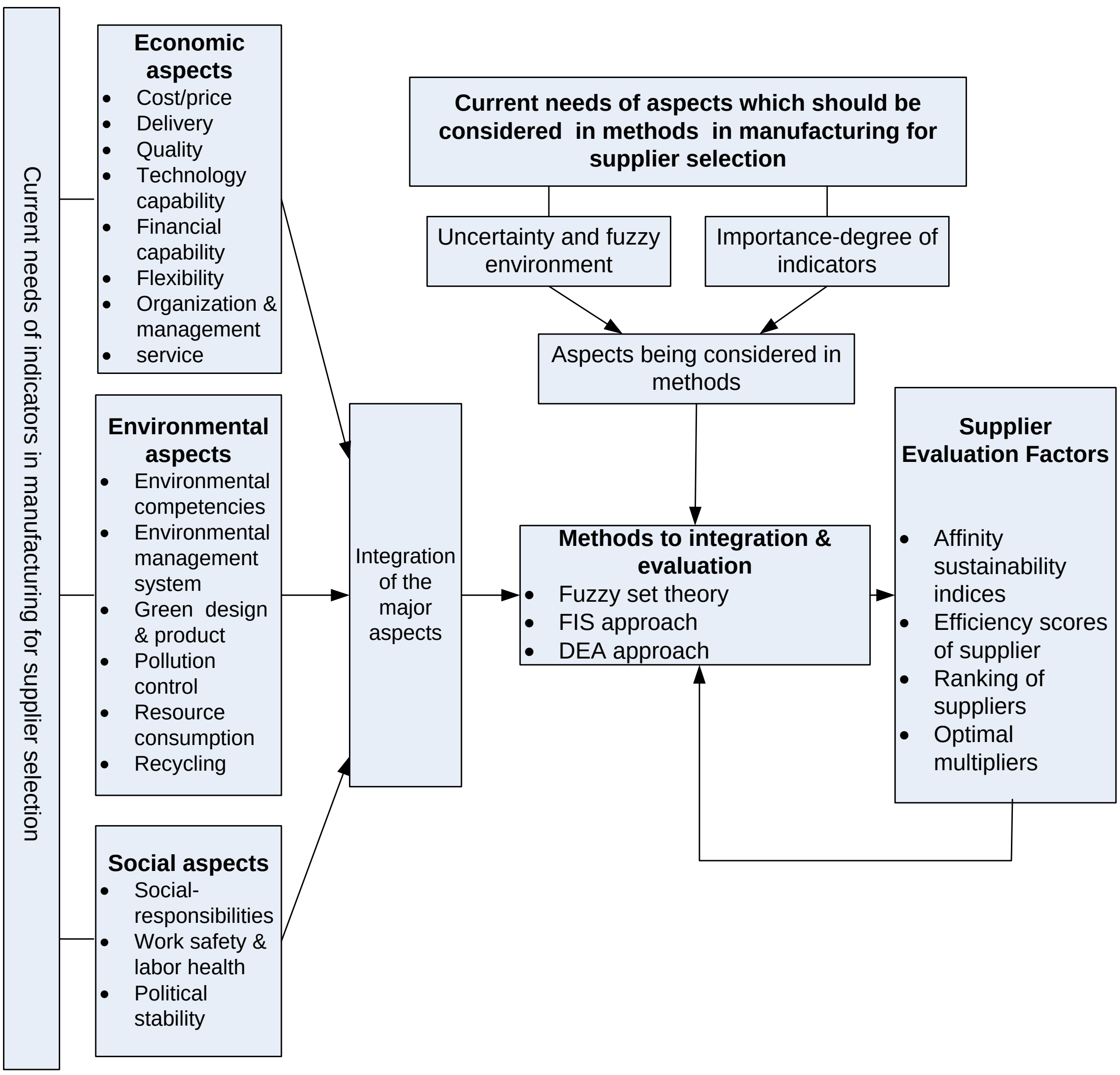


Figure 4.1: Sustainable supplier selection model.

The literature review was expanded to introduce some important issues in supplier selection problem that are being faced by manufacturers but not yet adequately considered by researchers in this area. The primary concern was contemplating the sustainability merits for supplier performance indicators in manufacturing. In fact, with the growing of knowledge on sustainability issues, the conventional supplier selection should be shifted to sustainable supplier selection. So, environmental and social merits must be included along with the economic merits for supplier selection (see Table 2.7). Other concern including two aspects which have been received attention recently in the existing supplier selection methods as mentioned in Chapter 2 (see Table 2.3). Firstly, how is to consider the various importance-degree of the performance indicators for supplier selection in the prevailing situation? Secondly, how is to handle the uncertain information in the supplier selection process? However, there are some basic decision making methods that are not being considered by the past researchers along with the mentioned aspects (viz. "handling with uncertain information" and "consideration of the relative importance of performance indicators"). For example, DEA technique has been adopted as an applicable tool for supplier selection as mentioned in Chapter 2 (see Section 2.3). However DEA technique is a popular standalone approach in supplier selection until 2008 (W. Ho et al., 2010), but it has not been much applied in recent years. This is because of the shortcomings of DEA approach with consideration of the mentioned aspects. So, this research work focused on the shortcomings of the DEA considering the aforementioned concerns to establish useful decision model for supplier selection. Fuzzy set theory and fuzzy inference system (FIS) are integrated with DEA as a developed method in this work.

4.1.1 Model Assumptions for this Model

In order to clarify this model, several important assumptions have been made:

i. The model is best suited for industries those are concerned about the sustainability issues in their supplier selection process.
ii. The model is best suited for single sourcing environments.
iii. The model is applicable for industries with any number of supplier performance indicators in accordance with the needs of the firms.
iv. The model is applicable for large, medium, and small companies and there is no limitation about the number of candidate suppliers.
v. Technological development, particularly the application of advanced data processing tools can be facilitated the sustainable supplier selection procedure.

4.2 Proposed Integrated FIS-DEA Method

To execute the proposed model, there is a need to develop a modified method. Hence, the integrated FIS-DEA method is proposed in this research. To show the structure of the proposed FIS-DEA method, an overall block diagram of it is shown in Figure 4.2. The fuzzy data are produced by MATLAB programming software to pass to the method through two approaches (FIS and DEA). Finally, Lingo software is applied to execute the proposed method. As seen in Figure 4.2, the conceptual model along with the proposed method can be programmed for industry using the user-friendly software (MATLAB and Lingo Software).

The proposed evaluation and selection method is executed through four phases, each of which is further described below.

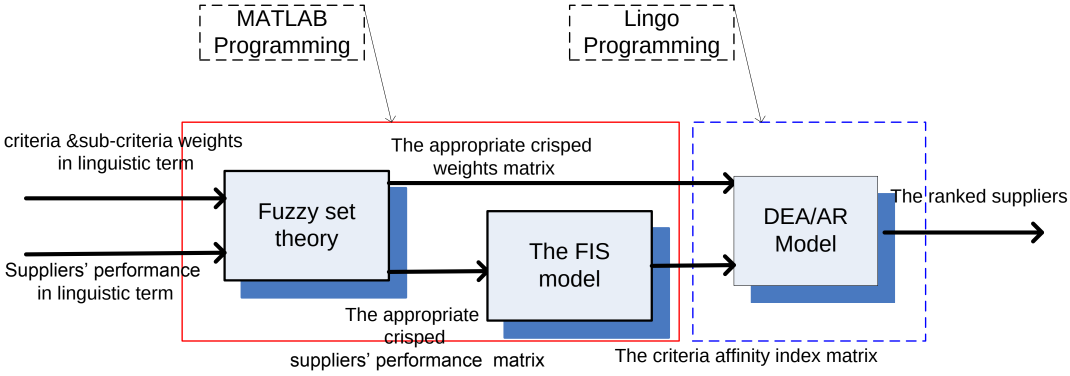


Figure 4.2: The block diagram of the proposed FIS-DEA method.

4.2.1 Database Building

As mentioned earlier through an intensive and up-to-date literature review, Table 2.1, Table 2.2, Table 2.3, and Table 2.4 were produced to derive the existing supplier performance indicators.

The indicators are classified into economic, environmental, and social groups for sustainable supplier selection. Then, the more popular indicators in each group are considered to prepare the questionnaires. The necessary data to pass into the proposed method are "relative importance of performance indicators" and "the suppliers' performance with respect to these indicators". So, the related questionnaires are designed based on these two dimensions. It is worthy to note that, there is no limitation on the number of performance indicators and any extra indicators can be added for each of economic, environmental, and social groups in questionnaires (See Appendix-A).

The data collection method was described in Chapter 3. The data was collected through the purchasing managers as decision makers from two countries (See Appendix-B and Appendix-C). As it was mentioned in Chapter 3, two test beds designed based on experts' knowledge in procurement teams to execute the proposed method. The related information to design the test beds including the number of performance indicators, the weight of indicators, the number of candidate suppliers, and suppliers' rating with respect to the indicators were gathered. All of these data and information was collected in linguistic terms based on experts' knowledge.

4.2.2 Data Processing on Data under Fuzzy Theory

To process the raw data and prepare the inputs for the proposed hybrid method, some essential preliminary theories as explained in Chapter 2 were taken into account. First, two groups of linguistic variables were utilized to show the decisions makers' preferences for the performance indicators' (criteria and sub-criteria) weights and the supplier's performance with respect to sub-criteria. Then, the fuzzy membership functions of these linguistic variables were determined by using fuzzy set theory as shown in Table 4.1 and Table 4.2, respectively. It is noteworthy that, the triangular membership function is utilized in this work because of linear interpolation between fuzzy set elements. The two related membership functions of the linguistic variable groups are developed by MATLAB programming as shown in Figure 4.3 and Figure 4.4.

Table 4.1: The linguistic terms for indicators' (criteria and sub-criteria) weights.

Linguistic variables	Corresponding triangular fuzzy number
Weak Important (WI)	(0, 0.17, 0.34)
Low Moderate Important (LMI)	(0.17, 0.34, 0.5)
Moderate Important (MI)	(0.34, 0.5, 0.67)
Strong Important (SI)	(0.5, 0.67, 0.84)
Extreme Important (EI)	(0.67, 0.84, 1.0)

Table 4.2: The linguistic terms for supplier's performance with respect to sub-criteria.

Linguistic variables	Corresponding triangular fuzzy number
Weakly Preferred (WP)	(0, 1.67, 3.34)
Low Moderately Preferred (LMP)	(1.67, 3.34, 5.00)
Moderately Preferred (MP)	(3.34, 5.00, 6.67)
Strongly Preferred (SP)	(5.00, 6.67, 8.34)
Extremely Preferred (EP)	(6.67,8.34, 10.0)

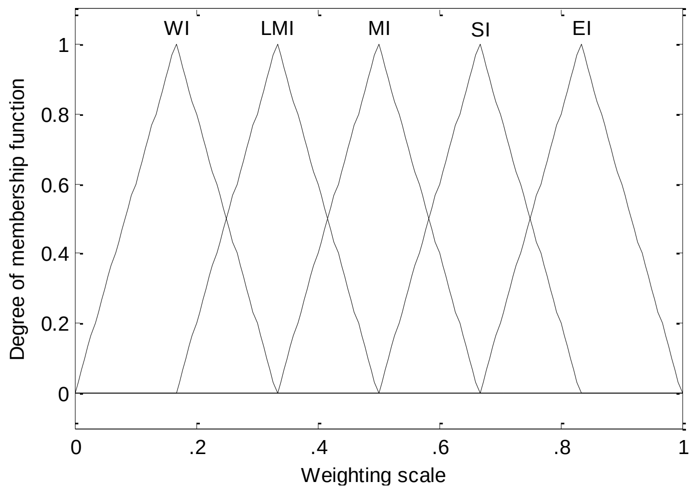


Figure 4.3: Membership functions for the weights of criteria and sub-criteria (Legends used from Table 4.1).

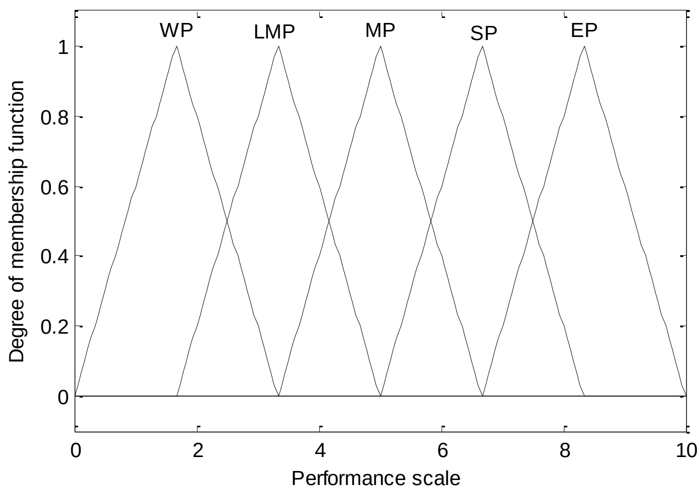


Figure 4.4: Membership functions for the supplier's performance (Legends used from Table 4.2).

Regarding to Figure 4.3 and Figure 4.4 for example, “Weak Important” can be represented as (0, 0.17, 0.34) and “strongly preferred” can be represented as (5.00, 6.67, 8.34).

It is worthwhile to say that to execute the proposed method all of the sub-criteria were preferred in larger-is-better orientation. So, if there is any negative sub-criterion (smaller-is-better) it must be changed in a way that it would be a positive criterion. For example, “cost” is a negative sub-criterion (smaller-is-better). To change “cost” to larger-better criterion, it can be replaced by the “profit” which is calculated by subtracting the cost from income.

4.2.2.1 Processing of the Suppliers’ Performance Data

To utilize the related suppliers’ performances data as inputs for the proposed method, suppose that there are n sub-criteria ($j = 1,2,..g, g+1,\ldots,h, h+1,..,n-1, n$), p suppliers ($s = 1,2,\ldots p$) and K decision makers. The decisions makers’ preferences for each supplier’s performance with respect to sub-criteria are solicited as,

$$sp_s = [\tilde{r}_{jk}]_{n\times K} \qquad k = 1,..,K \qquad j = 1,2,..g, g+1,\ldots,h, h+1,..,n-1, n \tag{4.1}$$

where, $\tilde{r}_{jk}$ is the related fuzzy number for the performance of each supplier with respect to j th sub-criteria based on k th decision maker. So, sp_s shows the performance of s th supplier with respect to all of n sub-criteria based on K decision makers.

To aggregate K decision makers’ opinions for each sub-criterion, the aggregated fuzzy number considering (4.2) can be defined as equation (4.3).

$$\tilde{R}_E = (a_E, b_E, c_E) \qquad E = 1,2,\ldots,q \tag{4.2}$$

$$\begin{aligned}
&\tilde{R} = (a,b,c) \\
&st. \\
&a = \frac{1}{q}\sum_{E=1}^{q} a_E \qquad ,b = \frac{1}{q}\sum_{E=1}^{q} b_E \\
&c = \frac{1}{q}\sum_{E=1}^{q} c_E
\end{aligned} \tag{4.3}$$

where, $\tilde{R}_E$ shows the E th fuzzy number and $\tilde{R}$ refers to aggregated one.

By applying equation (4.2) for every row of matrix (4.1) the aggregation is obtained as shown in (4.4). For example, the fuzzy numbers $\tilde{r}_{11}, \tilde{r}_{12,}, \ldots, \tilde{r}_{1K}$ are aggregated to $\tilde{R}_{11}$.

$$sp_s = [\tilde{r}_{jk}]_{n\times K} = \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1K} \\ \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2K} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{r}_{g1} & \tilde{r}_{g2} & \cdots & \tilde{r}_{gK} \\ \tilde{r}_{(g+1)1} & \tilde{r}_{(g+1)2} & \cdots & \tilde{r}_{(g+1)K} \\ \tilde{r}_{(g+2)1} & \tilde{r}_{(g+2)2} & \cdots & \tilde{r}_{(g+2)K} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{r}_{h1} & \tilde{r}_{h2} & \vdots & \tilde{r}_{hK} \\ \tilde{r}_{(h+1)1} & \tilde{r}_{(h+1)2} & \cdots & \tilde{r}_{(h+1)K} \\ \tilde{r}_{(h+2)1} & \tilde{r}_{(h+2)2} & \cdots & \tilde{r}_{(h+2)K} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{r}_{n1} & \tilde{r}_{n2} & \cdots & \tilde{r}_{nK} \end{bmatrix} \begin{matrix} \Rightarrow \\ \Rightarrow \\ \vdots \\ \Rightarrow \\ \Rightarrow \\ \Rightarrow \\ \vdots \\ \Rightarrow \\ \Rightarrow \\ \Rightarrow \\ \vdots \\ \Rightarrow \end{matrix} \begin{bmatrix} \tilde{R}_{11} \\ \tilde{R}_{21} \\ \vdots \\ \tilde{R}_{g1} \\ \tilde{R}_{(g+1)1} \\ \tilde{R}_{(g+2)1} \\ \vdots \\ \tilde{R}_{h1} \\ \tilde{R}_{(h+1)1} \\ \tilde{R}_{(h+2)1} \\ \vdots \\ \tilde{R}_{n1} \end{bmatrix}_{n\times 1} = R_1 \tag{4.4}$$

Where, R_1 refers to fuzzy decision matrix of the first supplier's performance.

This procedure is repeated for each of the suppliers and there is no limitation about the number of suppliers. Finally the fuzzy decision matrix (FDM) has been obtained as,

$$FDM = \begin{bmatrix} R_1 & R_2 & \ldots & R_p \end{bmatrix}^T = \begin{bmatrix} \tilde{R}D_{sj} \end{bmatrix}_{p\times n} \qquad s = 1,2,\ldots,p \qquad j = 1,2,\ldots,n \tag{4.5}$$

Where, T refers to transpose shows the transposition of the matrix and $\tilde{R}D_{sj}$ refers to the aggregated arrays of s th supplier's performance with respect to j th sub-criteria.

Now, the aggregated fuzzy decision matrix of the supplier's performances with respect to sub-criteria are defuzzified in the desired crisp numbers as shown in (4.6).

$$CD = [R_{jk}]^T{}_{p\times n} = \begin{bmatrix} R_{11} & R_{12} & \dots & R_{1p} \\ R_{21} & R_{22} & \dots & R_{2p} \\ \vdots & \vdots & \vdots & \vdots \\ R_{g1} & R_{g2} & \dots & R_{gp} \\ R_{(g+1)1} & R_{(g+1)2} & \dots & R_{(g+1)p} \\ R_{(g+2)1} & R_{(g+2)2} & \dots & R_{(g+2)p} \\ \vdots & \vdots & \vdots & \vdots \\ R_{h1} & R_{h2} & \dots & R_{hp} \\ R_{(h+1)1} & R_{(h+1)2} & \dots & R_{(h+1)p} \\ R_{(h+2)1} & R_{(h+2)2} & \dots & R_{(h+2)p} \\ \vdots & \vdots & \vdots & \vdots \\ R_{n1} & R_{n2} & \dots & R_{np} \end{bmatrix}^T \quad (4.6)$$

where, R_{jk} refers to the aggregated and defuzzified arrays of supplier's performances with respect to j th sub-criterion of k th decision maker and CD is the defuzzified matrix of all suppliers 'performances.

4.2.2.2 Processing of the Indicators' Weights Data

To design the proposed method, decision makers' opinions about the relative importance of both criteria and sub-criteria are utilized. To show the importance weight of criteria and sub-criteria, the linguistic variables are used and converted to fuzzy numbers as shown in Figure 4.3. The decision makers express their preferences about the relative importance of each criterion in comparison with other criteria (wc) and also each sub-criterion in comparison with other sub-criteria in its related criteria group (wsc) as shown in (4.7) and (4.8), respectively.

$$wc = [\tilde{w}c_{ik}]_{3*K} \qquad k = 1,\dots,K \qquad i = 1,2,3 \quad (4.7)$$

$$wsc = [\tilde{w}sc_{jk}]_{n*K} \qquad k = 1,\dots,K \qquad j = 1,2,..g, g+1,\dots,h, h+1,..,n-1, n \quad (4.8)$$

where, $\tilde{w}c_{ik}$ is the relative importance of i th criterion based on k th decision maker and $\tilde{w}sc_{ik}$ is the relative importance of j th sub-criterion based on k th decision maker. To calculate the relative importance of each sub-criterion in comparison with all other sub-criteria, the importance weight of each sub-criterion must be multiplied with the importance weight of its related criterion according to each decision maker's preference as shown in equation (4.9).

$$fw = \begin{bmatrix}
\dfrac{\begin{matrix} \tilde{w}sc_{11} * \tilde{w}c_{11} \\ wsc_{21} * \tilde{w}c_{11} \\ \vdots \\ \tilde{w}sc_{g1} * \tilde{w}c_{11} \end{matrix}}{\tilde{W}_{11}} & \dfrac{\begin{matrix} \tilde{w}sc_{12} * \tilde{w}c_{12} \\ \tilde{w}sc_{22} * \tilde{w}c_{12} \\ \vdots \\ \tilde{w}sc_{g2} * \tilde{w}c_{12} \end{matrix}}{\tilde{W}_{12}} & \begin{matrix} \cdots \\ \cdots \\ \vdots \\ \cdots \end{matrix} & \dfrac{\begin{matrix} \tilde{w}sc_{1K} * \tilde{w}c_{1K} \\ \tilde{w}sc_{2K} * \tilde{w}c_{1K} \\ \vdots \\ \tilde{w}sc_{gK} * \tilde{w}c_{1K} \end{matrix}}{\tilde{W}_{1K}} \\
\dfrac{\begin{matrix} \tilde{w}sc_{(g+1)1} * \tilde{w}c_{21} \\ \tilde{w}sc_{(g+2)1} * \tilde{w}c_{21} \\ \vdots \\ \tilde{w}sc_{h1} * \tilde{w}c_{21} \end{matrix}}{\tilde{W}_{21}} & \dfrac{\begin{matrix} \tilde{w}sc_{(g+1)2} * \tilde{w}c_{22} \\ \tilde{w}sc_{(g+2)2} * \tilde{w}c_{22} \\ \vdots \\ \tilde{w}sc_{h2} * \tilde{w}c_{22} \end{matrix}}{\tilde{W}_{22}} & \begin{matrix} \cdots \\ \cdots \\ \vdots \\ \cdots \end{matrix} & \dfrac{\begin{matrix} \tilde{w}sc_{(g+1)K} * \tilde{w}c_{2K} \\ \tilde{w}sc_{(g+2)K} * \tilde{w}c_{2K} \\ \vdots \\ \tilde{w}sc_{hK} * \tilde{w}c_{2K} \end{matrix}}{\tilde{W}_{2K}} \\
\dfrac{\begin{matrix} \tilde{w}sc_{(h+1)1} * \tilde{w}c_{31} \\ \tilde{w}sc_{(h+2)1} * \tilde{w}c_{31} \\ \vdots \\ \tilde{w}sc_{n1} * \tilde{w}c_{31} \end{matrix}}{\tilde{W}_{31}} & \dfrac{\begin{matrix} \tilde{w}sc_{(h+1)2} * \tilde{w}c_{32} \\ \tilde{w}sc_{(h+2)2} * \tilde{w}c_{32} \\ \vdots \\ \tilde{w}sc_{n2} * \tilde{w}c_{32} \end{matrix}}{\tilde{W}_{32}} & \begin{matrix} \cdots \\ \cdots \\ \vdots \\ \cdots \end{matrix} & \dfrac{\begin{matrix} \tilde{w}sc_{(h+1)K} * \tilde{w}c_{3K} \\ \tilde{w}sc_{(h+2)K} * \tilde{w}c_{3K} \\ \vdots \\ \tilde{w}sc_{nK} * \tilde{w}c_{3K} \end{matrix}}{\tilde{W}_{3K}}
\end{bmatrix} \tag{4.9}$$

where, fw is the multiplied matrix of the criteria and sub-criteria weights.

To reduce the computational burden in the proposed method the obtained fuzzy weights of sub-criteria which shown in (4.9) are combined into three criteria groups (economic, environmental, and social). In fact, decision maker's opinion for sub-criteria weights aggregate to decision maker's opinion for criteria weights. Therefore, by applying the equation (4.10), the fuzzy weights matrix (fw) is converted to a matrix which includes $\tilde{W}$ arrays as presented in equation (4.10).

$$FW = [\tilde{W}_{ik}]_{3*K} \qquad k = 1,..,K \qquad i = 1,2,3 \tag{4.10}$$

where, $\tilde{W}_{ik}$ is the aggregated arrays of fw matrix into i th criterion based on k th decision maker and FW is the aggregated matrix of fw matrix.

The importance weights are reflected in the proposed FIS-DEA method through two steps. First, the arrays of fuzzy weights matrix (4.9) are defuzzified to the crisp weights by using the COA method as shown in (4.11).

$$CW = [W_{ik}]_{3*K} \qquad k = 1,..,K \qquad i = 1,2,3 \tag{4.11}$$

where, W_{ik} is the defuzzified form of $\tilde{W}_{ik}$ and CW is the defuzzified form of FW matrix.

Second, for every pair of criteria the ratio of their weights based on decision makers' opinions are calculated as shown in equation (4.12) and the maximum and minimum of each column are derived as upper and lower bound of pair criteria weights ratio to apply in weight constraints in the models (Takamura & Tone, 2003).

$$R_{CW^T} = \begin{bmatrix} \frac{W_{11}}{W_{12}} & \frac{W_{12}}{W_{13}} & \frac{W_{11}}{W_{13}} \\ \frac{W_{21}}{W_{22}} & \frac{W_{22}}{W_{23}} & \frac{W_{21}}{W_{23}} \\ \vdots & \vdots & \vdots \\ \frac{W_{K1}}{W_{K2}} & \frac{W_{K2}}{W_{K3}} & \frac{W_{K1}}{W_{K3}} \end{bmatrix}_{K*3} \tag{4.12}$$

where, R_{CW^T} is the ratio matrix of criteria weights to prepare the weight restriction for the proposed method. As seen in (4.12), the first array ($\frac{W_{11}}{W_{12}}$) shows the ratio of economic criteria ($i = 1$) and environmental criteria based on the first decision maker and so on. For example, in the first column of R_{CW^T} there are the ratio of economic criteria and environmental criteria based on $k = 1,2,...K$ decision makers. To achieve the lower and upper bounds for weight ratio of paired criteria, the minimum and maximum in each column must be derived. These bounds are shown in Table 4.3 for $k = 1,2,...K$ decision makers.

Table 4.3: The lower and upper bounds for weight ratio of paired criteria.

		Economic/Environmental	Environmental/ Social	Economic /social
Criteria bounds	Minimum	$A_L = \min_k \frac{W_{ki} \ for \ \ i=1}{W_{ki} \ for \ \ i=2}$	$B_L = \min_k \frac{W_{ki} \ for \ \ i=2}{W_{ki} \ for \ \ i=3}$	$C_L = \min_k \frac{W_{ki} \ for \ \ i=1}{W_{ki} \ for \ \ i=3}$
	Maximum	$A_u = \max_k \frac{W_{ki} \ for \ \ i=1}{W_{ki} \ for \ \ i=2}$	$B_u = \max_k \frac{W_{ki} \ for \ \ i=2}{W_{ki} \ for \ \ i=3}$	$C_u = \max_k \frac{W_{ki} \ for \ \ i=1}{W_{ki} \ for \ \ i=3}$

4.2.3 Building and Executing the Modular FIS System

The systematic process based on a modular FIS approach is proposed to rate the affinity indices of candidate suppliers with sustainability. The methodological flow of the modular FIS design is shown in Figure 4.5. The proposed modular FIS system explicitly shows a mathematical function in which the image of n elements (n sub-criteria) is the final result of the system. Therefore, it is supposed that the value y is a function f of n independent variables as shown in (Equation 4.13).

$$y = f(x_{1,} x_2, x_3, ..., x_n) \tag{4.13}$$

The processed suppliers' performance data which were derived from (4.4) are implemented for using as input variables ($x_{1,} x_2, ...x_g, x_{g+1}, ..,.x_h, x_{h+1}, ...,, x_n$) into the FIS systems. These inputs are categorized into economic, environmental, and social groups as shown in Figure 4.6.

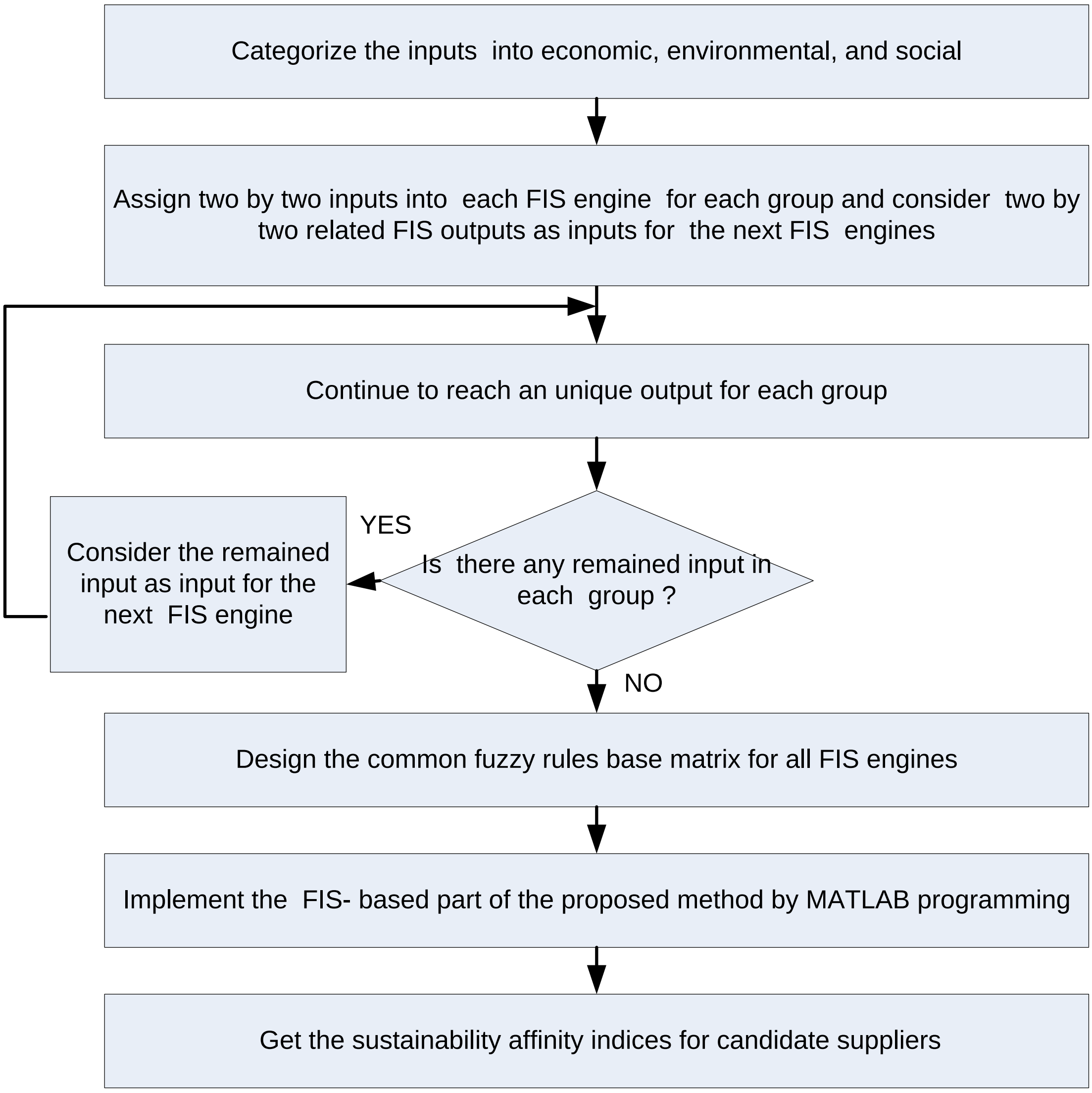
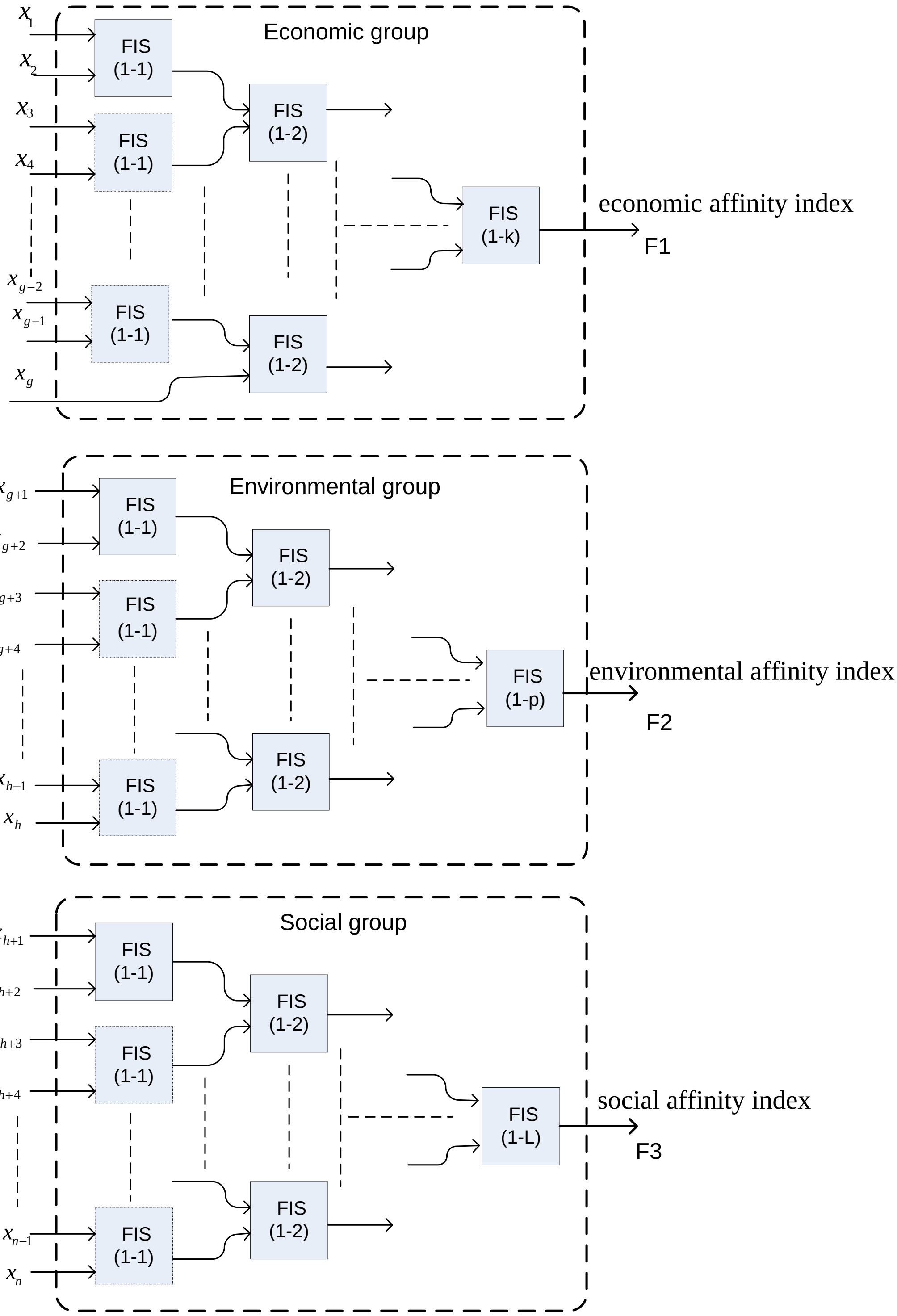


Figure 4.5: The methodological flow of the modular FIS of the proposed method.

Usually, for FIS systems, the maximum number of inputs is not considered more than two elements in order to decrease the number of fuzzy rules and design the rules more simply. Hence, this has been taken into account in designing the modular FIS system for the proposed method. So, each two by two of inputs are assigned into each FIS engine for each group and consider two by two related FIS outputs as inputs for the next FIS engines. It is noted that after selecting two by two of input variables in each group, if one of the input variables remains (when the number of input variables is odd), consider the remaining input variable as output variable for one of the FIS engines in that group as noted in Figure 4.6 for economic group. Using of FIS systems in this process is continued until the number of outputs for each of three groups equal to 1. The modular FIS system has three output variables namely economic affinity index, environmental affinity index, and social affinity index (Figure 4.6).



Note :the number of input variables is supposed for economic group odd and for two other groups even

Figure 4.6: Sustainability affinity indices of suppliers based on modular FIS approach.

To design a set of the fuzzy linguistic rules based on expert knowledge, it must be considered that each of the criteria is preferred to be larger-is-better. The rules are adjusted on the preference of decision makers to have the appropriate ratings of affinity indices. Also, the rules are designed on the basis of averaging concept for each FIS system as shown in Table 4.4.

Table 4.4: The fuzzy rule base matrix for proposed FIS-DEA method.

		The first input				
		WP	LMP	MP	SP	EP
The second input	WP	WP	WP	LMP	LMP	MP
	LMP	WP	LMP	LMP	MP	MP
	MP	LMP	LMP	MP	MP	SP
	SP	LMP	MP	MP	SP	SP
	EP	MP	MP	SP	SP	EP

The designed rules cover the changes of suppliers' performance completely and map their numeric scale of inputs to their numeric scale in outputs. The modular FIS system has three output variables namely economic affinity index, environmental affinity index, and social affinity index (see Figure 4.6*)*.

It is worth to note that, the proposed FIS part of the proposed method is repeated for every candidate suppliers to get their affinity indices.

4.2.4 Ranking the Suppliers by using DEA

To rank the candidate suppliers, an assurance region of DEA technique (DEA/AR) is implemented in the proposed method. The methodological flow of the DEA/AR is shown in Figure 4.7. To execute any DEA approach, the input and output variables must be defined. So, the affinity indices from the modular FIS system are settled in the criteria affinity index matrix (CAI) (Equation 4.14) as output variables in the proposed DEA model. The arrays of CAI matrix are fed into DEA model for every supplier and to calculate the relative efficiency of suppliers a dummy input is applied.

$$CAI = [c_{i\times s}]^T{}_{p\times 3} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ \vdots & \vdots & \vdots \\ c_{s1} & c_{s2} & c_{s3} \end{bmatrix} \qquad s = 1,2,\ldots,p \qquad , i = 1,2,3 \tag{4.14}$$

where, $c_{i\times s}$ is the i th affinity index for s th supplier and CAI is the related matrix into affinity indices of criteria for each supplier.

By applying the upper and lower bound (Table 4.3), the weight restrictions are added as equation (2.14) to the DEA model.

$$A_L \le \frac{u_{s1}}{u_{s2}} \le A_u, \quad B_L \le \frac{u_{s2}}{u_{s3}} \le B_u, \quad C_L \le \frac{u_{s1}}{u_{s3}} \le C_u \qquad s = 1,2,\ldots,p \tag{4.15}$$

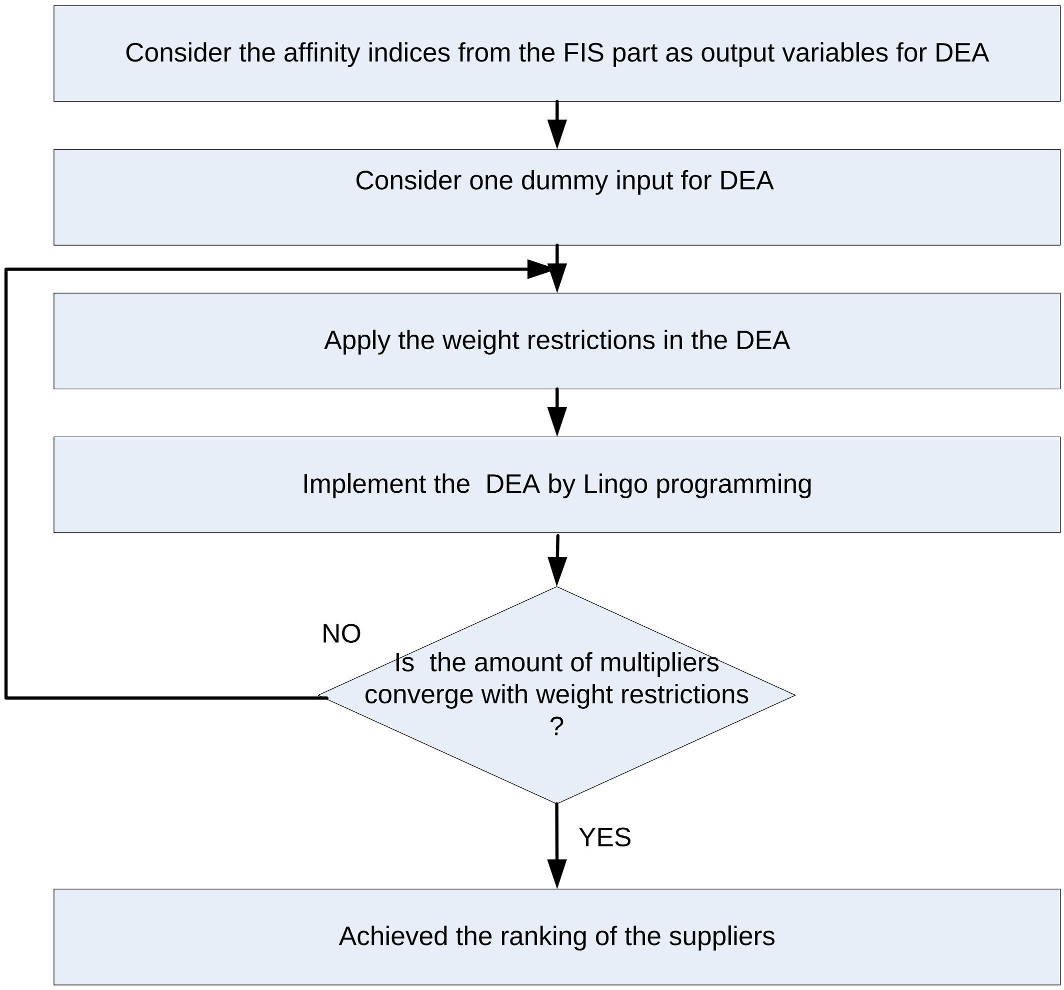


Figure 4.7: The methodological flow of the DEA/AR of the proposed method.

The processed data including suppliers' performance and weight restrictions are prepared by MATLAB programming software that is explained in chapter 5. Also, Lingo software is applied to execute the proposed method for getting the ranking results that is presented in chapter 5.

The proposed method is open ended to adapt any number of supplier selection criteria and candidate suppliers for today's manufacturing including small, medium and large enterprises.

4.3 The FIS-based Supplier Selection Approach

To discuss on research findings, this thesis suggests comparing the proposed method with existing supplier selection methods as seen in Figure 3.1. So, one of the newest ones (Amindoust, 2012) based on FIS approach is described as below.

To provide the inputs for this method, similar to the proposed method, the related data must be processed under fuzzy theory to pass into the FIS-based supplier selection method. This method is done through three stages and considering some adjusted fuzzy rules based; the ranking of suppliers are derived as shown in Figure 4.8.

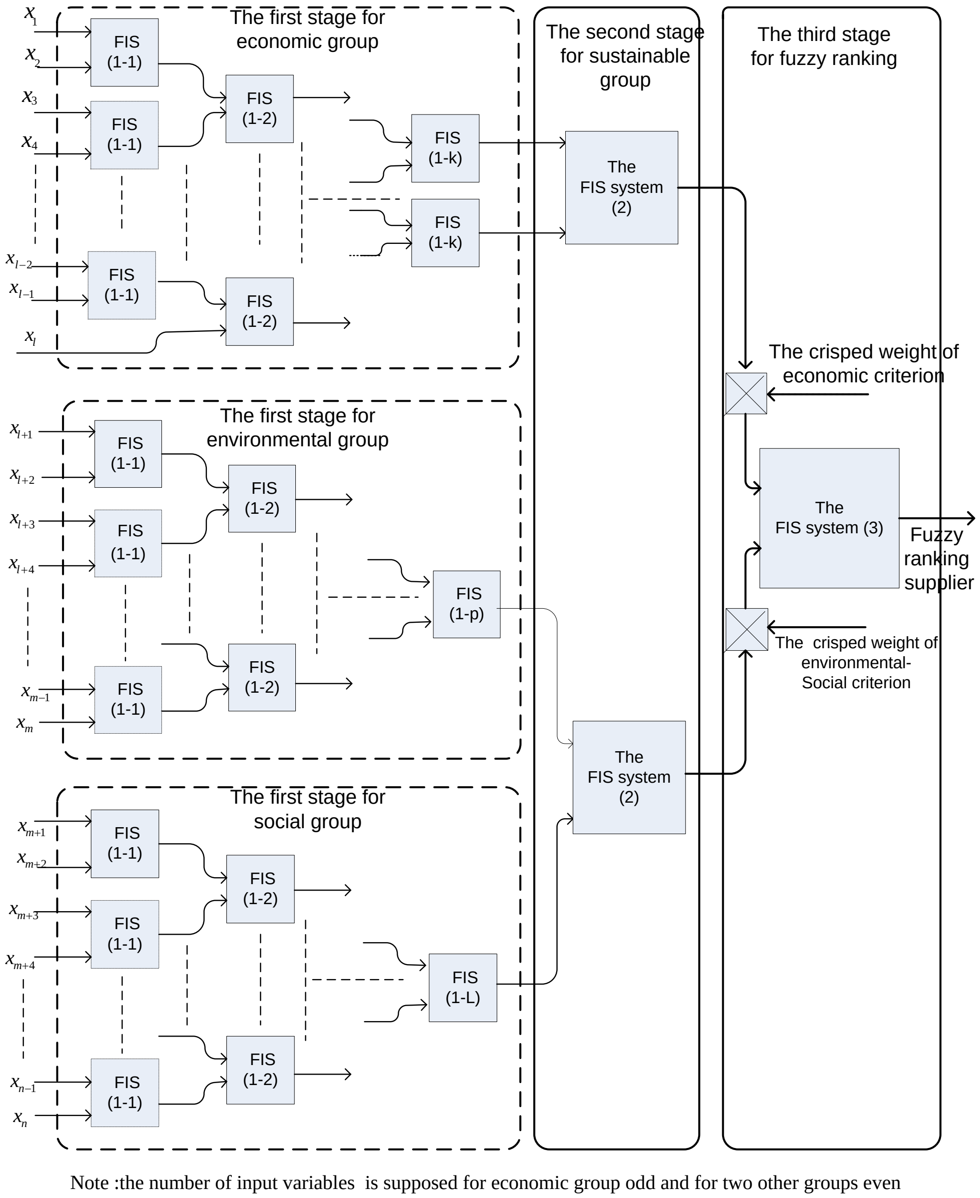


Figure 4.8: The schematic of the FIS-based supplier selection method.

The related suppliers' performance matrix which was shown in (4.1) is also applied here to prepare the inputs. Similar to supplier performance, for aggregating K decision makers' opinions for each sub-criterion's weights (wsc), by applying equation (4.3) for every row of matrix (4.8) the aggregation is obtained as shown in (4.16).

$$wsc=[\tilde{w}sc_{jk}]_{n*K}=\begin{bmatrix} \tilde{w}sc_{11} & \tilde{w}sc_{12} & \cdots & \tilde{w}sc_{1K} \\ wsc_{21} & \tilde{w}sc_{22} & \cdots & \tilde{w}sc_{2K} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{w}sc_{g1} & \tilde{w}sc_{g2} & \cdots & \tilde{w}sc_{gK} \\ & & & \\ \tilde{w}sc_{(g+1)1} & \tilde{w}sc_{(g+1)2} & \cdots & \tilde{w}sc_{(g+1)K} \\ \tilde{w}sc_{(g+2)1} & \tilde{w}sc_{(g+2)2} & \cdots & \tilde{w}sc_{(g+2)K} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{w}sc_{h1} & \tilde{w}sc_{h2} & \cdots & \tilde{w}sc_{hK} \\ & & & \\ \tilde{w}sc_{(h+1)1} & \tilde{w}sc_{(h+1)2} & \cdots & \tilde{w}sc_{(h+1)K} \\ \tilde{w}sc_{(h+2)1} & \tilde{w}sc_{(h+2)2} & \cdots & \tilde{w}sc_{(h+2)K} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{w}sc_{n1} & \tilde{w}sc_{n2} & \cdots & \tilde{w}sc_{nK} \end{bmatrix} \begin{matrix} \Rightarrow \\ \Rightarrow \\ \vdots \\ \Rightarrow \\ \\ \Rightarrow \\ \Rightarrow \\ \vdots \\ \Rightarrow \\ \\ \Rightarrow \\ \Rightarrow \\ \vdots \\ \Rightarrow \end{matrix} \begin{bmatrix} \tilde{W}SC_{11} \\ \tilde{W}SC_{21} \\ \vdots \\ \tilde{W}SC_{g1} \\ \\ \tilde{W}SC_{(g+1)1} \\ \tilde{W}SC_{(g+2)1} \\ \vdots \\ \tilde{W}SC_{h1} \\ \\ \tilde{W}SC_{(h+1)1} \\ \tilde{W}SC_{(h+2)1} \\ \vdots \\ \tilde{W}SC_{(n)1} \end{bmatrix} = WSC \tag{4.16}$$

where, the decision maker preferences on sub-criteria weights in wsc matrix are aggregated into WSC for each sub-criterion.

To calculate the input variables ($x_{1,} x_2,..x_{g-1}, x_g,..,x_{h-1}, x_h,...,x_{n-1}, x_n$) for the FIS-based method, the fuzzy aggregated supplier performances (4.5) is multiplied by the fuzzy aggregated importance weight of each sub-criterion (4.16) as shown in (4.17). Then, the obtained fuzzy numbers are defuzzified to the desired crisp numbers as input variables for the FIS systems in the first stage.

$$\tilde{x}_{n\times 1}=\begin{bmatrix} \tilde{W}SC_{11}*\tilde{R}_{11} \\ \tilde{W}SC_{21}*\tilde{R}_{21} \\ \vdots \\ \tilde{W}SC_{g1}*\tilde{R}_{g1} \\ \tilde{W}SC_{(g+1)1}*\tilde{R}_{(g+1)1} \\ \tilde{W}SC_{(g+2)1}*\tilde{R}_{(g+2)1} \\ \vdots \\ \tilde{W}SC_{h1}*\tilde{R}_{h1} \\ \\ \tilde{W}SC_{(h+1)1}*\tilde{R}_{(h+1)1} \\ \tilde{W}SC_{(h+2)1}*\tilde{R}_{(h+2)1} \\ \vdots \\ \tilde{W}SC_{(n)1}*\tilde{R}_{n1} \end{bmatrix} \tag{4.17}$$

where, $\tilde{x}_{n\times 1}$ shows the prepared inputs for the FIS-based method which obtained from multiplication of supplier's performances with WSC matrix.

First stage is continued and the FIS systems are applied until the number of FIS systems' outputs for economic group is equal to 2 and for both environmental and social groups equal to 1. So, four inputs including the two outputs of economic group, the one output of environmental group, and the one output of social group are considered for two FIS systems in the second stage. In the first and second stages, five linguistic variables are utilized to show the decisions makers' preferences for the supplier's performance with respect to sub-criteria as shown in Table 4.2. But, in the third stage, seven membership functions are applied to show the decisions makers' preferences as shown in Table 4.5. The related membership functions of the linguistic variables are developed by MATLAB programming as shown in Figure 4.9.

Table 4.5: The linguistic terms for supplier's performance with respect to sub-criteria for the FIS-based method.

Linguistic variables	Corresponding triangular fuzzy number
Very Weakly Preferred (VWP)	(0.00, 12.5, 25)
Weakly Preferred (WP)	(12.5, 25, 37.5)
Low Moderately Preferred (LMP)	(25, 37.5, 50.0)
Moderately Preferred (MP)	(37.5, 50.0, 62.5)
High Moderately Preferred (HMP)	(50.0, 62.5, 75.0)
Strongly Preferred (SP)	(62.5, 75.0, 87.5)
Extremely Preferred (EP)	(75.0,87.5, 100.0)

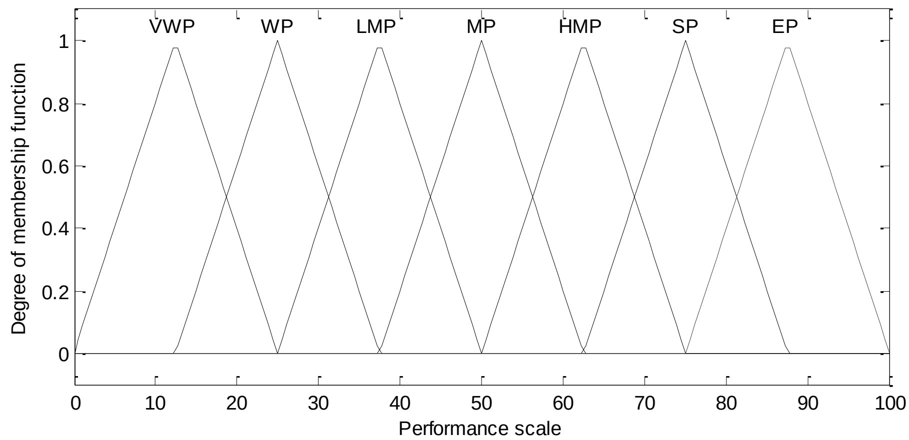


Figure 4.9: The membership functions in third stage of FIS-based method.

To begin the third stage, similar to the relative importance of each sub-criterion, for aggregating K decision makers' opinions for each criteria's weights (wc), by applying equation (4.3) for every row of matrix (4.17) the aggregation is obtained as shown in (4.18).

$$wc = [\tilde{w}c_{ik}]_{3*K} = \begin{bmatrix} \tilde{w}c_{11} & \tilde{w}c_{12} & \dots & \tilde{w}c_{1k} \\ \tilde{w}c_{21} & \tilde{w}c_{22} & \dots & \tilde{w}c_{2k} \\ \tilde{w}c31 & \tilde{w}c_{32} & \dots & \tilde{w}c_{3k} \end{bmatrix} \begin{matrix} \Rightarrow \\ \Rightarrow \\ \Rightarrow \end{matrix} \begin{bmatrix} \tilde{W}C_{11} \\ \tilde{W}C_{21} \\ \tilde{W}C_{31} \end{bmatrix} = WC \qquad k = 1,..,K \qquad i = 1,2,3 \tag{4.18}$$

where, WC shows the aggregated criteria weights for each criteria. Then, the fuzzy weight of economic criterion ($\tilde{W}C11$) is defuzzified to crisp number and multiplied by its related output value in the second stage**.** Also, the average between the weights of environmental ($\tilde{W}C21$) and social criteria ($\tilde{W}C31$) is defuzzified to crisp number and multiplied by its related output value in second stage (see Figure 4.8). It is noteworthy that the rules for the related FIS engines in the first and second stages are shown in Table 4.4 and for the third stage shown in Table 4.6.

Table 4.6: The fuzzy rule base matrix for FIS-based method in stage3.

		The first input				
		WP	LMP	MP	SP	EP
The second input	WP	VWP	WP	LMP	LMP	MP
	LMP	WP	LMP	LMP	MP	HMP
	MP	LMP	LMP	MP	HMP	SP
	SP	LMP	MP	HMP	SP	SP
	EP	MP	HMP	SP	SP	EP

This methodology (Figure 4.8) must be repeated for each candidate supplier to obtain its ranking. All of the aforementioned processes were done by applying MATLAB programming software.

CHAPTER 5

ANALYSIS, RESULT AND DISCUSSION

This chapter presents the various analyses carried out to fulfill the requirements of the research objectives laid down in Chapter 1. The overall results of the research are also summarized. It starts with the description of the analysis and results based on the definition of two new test beds. It is followed by a discussion on the research findings and the usefulness of the developed method. In fact, the performance validity of the proposed FIS-DEA method is presented through comparing this method with the existing supplier selection methods. An extensive range of programming is done by using MATLAB programming as shown in Appendix-E. Also the LINGO software has been used to execute the proposed FIS-DEA method which its programming for this research is shown in Appendix-F.

One of the newest supplier selection method based on FIS approach is implemented in this work to show the validation of the proposed FIS-DEA method. Some popular error measurement criteria are applied to present the amount of validation. To more discussion on research findings, this section suggests comparing the proposed supplier selection method and DEA-based methods. Since, this thesis is focused on DEA technique and its shortcomings; one of the intentions is to compare the outputs of the proposed method and traditional DEA technique. Also, to show the importance of weighting issue for the supplier selection indicators, the weight constraints are omitted in the proposed FIS-DEA method and the obtained results are compared by the proposed FIS-DEA method with consideration of weight restrictions.

5.1 Applicability of the Proposed FIS-DEA Method

The test bed illustration is applied in this research to confirm the compatibility between FIS and DEA approaches and to demonstrate the applicability and ease of use of the proposed FIS-DEA method. So, the feasibility of the proposed method is tested through two test beds which are designed based on experts' knowledge. First, two related questionnaires (Appendix-A) are passed into two groups of procurement team in two different companies to collect the data.

5.1.1 Execution of the First Test Bed

As mentioned in Chapter 3, the test bed scenario is applicable in decision making. A supplier selection test bed is designed based on experts' knowledge of an Iranian company. The company, namely Imen Soukht Sepahan, is producing a special alloy for petrol container for vehicles to prevent from catch fire which is named Deltas. This company is the leading producer of the mentioned alloy in Iran and this company is regarded as pioneer of innovation and creativity in this area since 5 years ago. So, there is a major need to evaluate performance rating of its potential suppliers from a sustainable point of view in future time. So, the procurement committee helped to design an appropriate test bed to show the feasibility of the method.

The questionnaires (Appendix-A) are including the decision makers' perceptions about the importance weights of the indicators (criteria and sub-criteria) and the suppliers' performance with respect to these indicators. The procurement committee having three decision makers namely, decision maker 1 (DM1), decision maker 2 (DM2), and decision maker 3 (DM3) from department of quality, department of purchasing, and an academic from university contributed in decision process to define the suitable criteria and subsequently identify the desirable candidates and ranking of them. They reviewed and verified the designed questionnaires in several meetings and discussed on the importance of the selection indicators and suppliers' performance. The information which has been derived through questionnaires as seen in Appendix-B is illustrated in Table 5.1and Table 5.2, respectively. As shown in Table 5.1, for example, the opinion of second decision maker (DM2) on the relative importance of environmental merits is SI (strongly Important) which its related fuzzy number equals to (0.5, 0.67, 0.84) according to Figure 4.3.

Table 5.1: Decision makers' opinions for criteria weights in the first test bed

		DM1	DM2	DM3
Criteria	Economic	EI(0.67, 0.84, 1.0)	EI(0.67, 0.84, 1.0)	MI(0.34, 0.5, 0.67)
	Environmental	EI(0.67, 0.84, 1.0)	SI(0.5, 0.67, 0.84)	MI(0.34, 0.5, 0.67)
	Social	EI(0.67, 0.84, 1.0)	MI(0.34, 0.5, 0.67)	MI(0.34, 0.5, 0.67)

As shown in Table 5.2, performance indicators with different weights are implemented in three criteria group. For example, the opinion of first decision maker (DM1) on the relative importance of F.C is moderately Important (MI) which is equal to (0.34, 0.5, 0.67). These Tables show that the economic merits have received more attention than environmental merits and also environmental merits have received more attention than social merits.

Table 5.2: Decision makers' opinions for sub-criteria weights in the first test bed

		DM1	DM2	DM3
Sub criteria	Cost	EI(0.67, 0.84, 1.0)	EI(0.67, 0.84, 1.0)	EI(0.67, 0.84, 1.0)
	Delivery on time	EI(0.67, 0.84, 1.0)	SI(0.5, 0.67, 0.84)	SI(0.5, 0.67, 0.84)
	Quality	EI(0.67, 0.84, 1.0)	EI(0.67, 0.84, 1.0)	SI(0.5, 0.67, 0.84)
	T. C	SI(0.5, 0.67, 0.84)	SI(0.5, 0.67, 0.84)	MI(0.34, 0.5, 0.67)
	F. C	MI(0.34, 0.5, 0.67)	MI(0.34, 0.5, 0.67)	LMI(0.167,0.34, 0.5)
	Flexibility	LMI(0.167,0.34, 0.5)	LMI(0.167,0.34, 0.5)	LMI(0.167,0.34, 0.5)
	O& C	MI(0.34, 0.5, 0.67)	MI(0.34, 0.5, 0.67)	MI(0.34, 0.5, 0.67)
	Service	SI(0.5, 0.67, 0.84)	MI(0.34, 0.5, 0.67)	LMI(0.167,0.34, 0.5)
	E. C	SI(0.5, 0.67, 0.84)	MI(0.34, 0.5, 0.67)	MI(0.34, 0.5, 0.67)
	E. M. S	EI(0.67, 0.84, 1.0)	SI(0.5, 0.67, 0.84)	MI(0.34, 0.5, 0.67)
	S. R	MI(0.34, 0.5, 0.67)	LMI(0.167,0.34, 0.5)	LMI(0.167,0.34, 0.5)
	W. S & L. H	LMI(0.167,0.34, 0.5)	LMI(0.167,0.34, 0.5)	LMI(0.167,0.34, 0.5)

Notes: Technological Capability= T.C; Financial Capability= F.C; Organization & Control= O&C; Environmental Competencies=E.C; Environmental Management System= E.M.S; Social Responsibility=S.R; Work Safety & Labor Health=W.S&L.H

The number of candidate suppliers in this test bed was 8. Decision makers' preferences about suppliers' performance with respect to performance indicators are shown in Table 5.3. For example, the opinions of DM1, DM2, and DM3 on the performance of first supplier with respect to Quality are MP, SP, and EP, respectively. The related fuzzy numbers to these linguistic ratings are (3.34, 5.00, 6.67), (5.00, 6.67, 8.34), and (6.67, 8.34, 10.0), respectively according to Figure 4.4.

Table 5.3: Decision makers' opinions on suppliers' performance in the first test bed

		DMs	Suppliers							
			1	2	3	4	5	6	7	8
Sub criteria	Cost	DM1:	EP	SP	EP	MP	SP	SP	MP	LMP
		DM2:	SP	MP	SP	SP	LMP	MP	LMP	LMP
		DM3:	SP	MP	EP	MP	MP	SP	MP	LMP
	Delivery on time	DM1:	SP	MP	SP	SP	MP	SP	LMP	WP
		DM2:	MP	MP	SP	MP	SP	MP	LMP	LMP
		DM3:	SP	SP	MP	MP	MP	LMP	MP	WP
	Quality	DM1:	MP	MP	SP	MP	MP	SP	LMP	LMP
		DM2:	SP	SP	EP	MP	MP	MP	LMP	LMP
		DM3:	EP	MP	SP	MP	MP	MP	LMP	LMP
	T. C	DM1:	MP	MP	SP	SP	LMP	SP	LMP	LMP
		DM2:	SP	MP	EP	MP	MP	MP	LMP	WP
		DM3:	SP	MP	SP	LMP	MP	MP	LMP	LMP
	F. C	DM1:	MP	LMP	SP	SP	LMP	MP	WP	LMP
		DM2:	MP	MP	LMP	SP	MP	MP	LMP	MP
		DM3:	MP	LMP	MP	LMP	MP	LMP	WP	LMP
	Flexibility	DM1:	MP	LMP	MP	LMP	MP	LMP	WP	WP
		DM2:	MP	MP	LMP	WP	LMP	LMP	WP	LMP
		DM3:	LMP	LMP	SP	WP	WP	WP	WP	LMP
	O & C	DM1:	MP	MP	MP	LMP	MP	MP	WP	WP
		DM2:	MP	LMP	MP	LMP	LMP	MP	LMP	LMP
		DM3:	MP	LMP	MP	MP	LMP	LMP	LMP	WP
	Service	DM1:	SP	MP	EP	MP	LMP	MP	LMP	WP
		DM2:	MP	LMP	SP	MP	MP	MP	MP	LMP
		DM3:	MP	MP	EP	SP	MP	SP	LMP	WP
	E. C	DM1	MP	EP	SP	LMP	MP	LMP	WP	LMP
		DM2	SP	SP	MP	LMP	LMP	LMP	WP	WP
		DM3	EP	SP	EP	MP	LMP	MP	WP	WP
	E. M. S	DM1	SP	SP	MP	MP	LMP	MP	WP	LMP
		DM2	MP	MP	MP	LMP	MP	LMP	WP	LMP
		DM3	MP	SP	MP	LMP	LMP	LMP	WP	LMP
	S. R	DM1	LMP	WP	MP	WP	LMP	WP	WP	WP
		DM2	LMP	LMP	LMP	WP	WP	LMP	LMP	LMP
		DM3	LMP	LMP	MP	WP	LMP	LMP	LMP	LMP
	W. S & L. H	DM1	LMP	LMP	MP	WP	LMP	LMP	WP	LMP
		DM2	LMP	WP	MP	WP	LMP	LMP	WP	LMP
		DM3	LMP	LMP	LMP	WP	WP	WP	LMP	WP

Table 5.3 as showing the decision makers' preference about suppliers' performance, is put as matrix arrays according to equation (4.1) and aggregated according to equation (4.2) and equation (4.3) as mentioned in section 4.2.2.1. Then, the obtained fuzzy decision (FD) matrix (4.5) is defuzzified according to COA method as shown in Table 5.4. For example from Table 5.3, the decision makers 'preferences on the performance of supplier 1 with respect to cost are EP (6.67, 8.34, 10.0), SP (5.00, 6.67, 8.34), and SP (5.00, 6.67, 8.34), respectively. So, the aggregation of them is (5.56, 7.23, 8.89). This fuzzy number is defuzzified based on COA to crisp number

which equals to 7.22 as seen in Table 5.4. All of these calculations have been done by MATLAB programming as shown in Appendix-E in “Prepare of the inputs for FIS-DEA approach” part.

Table 5.4: Prepared inputs for the modular FIS system in the first test bed

		Suppliers							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Sub criteria	Cost	7.2222	5.5556	7.7778	5.5556	5	6.1111	4.4444	3.3333
	Delivery on time	6.1111	5.5556	6.1111	5.5556	5.5556	5	3.8889	2.2222
	Quality	6.6667	5.5556	7.2222	5	5	5.5556	3.3333	3.3333
	T. C	6.1111	5	7.2222	5	4.4444	5.5556	3.3333	2.7778
	F. C	5	3.8889	5	5.5556	4.4444	4.4444	2.2222	3.8889
	Flexibility	4.4444	3.8889	5	2.2222	3.3333	2.7778	1.6667	2.7778
	O& C	5	3.8889	5	3.8889	3.8889	4.4444	2.7778	2.2222
	Service	5.5556	4.4444	7.7778	5.5556	4.4444	5.5556	3.8889	2.2222
	E. C	6.6667	7.2222	6.6667	3.8889	3.8889	3.8889	1.6667	2.2222
	E. M. S	5.5556	6.1111	5	3.8889	3.8889	3.8889	1.6667	3.3333
	S. R	3.3333	2.7778	4.4444	1.6667	2.7778	2.7778	2.7778	1.6667
	W. S & L. H	3.3333	2.7778	4.4444	1.6667	2.7778	2.2222	2.7778	1.6667

The arrays of aforementioned matrix were passed to the modular FIS system to get the sustainability affinity indices. To show the structure of rule viewers getting from MATLAB Software for the modular FIS system which presents the roadmaps of FIS systems, one of the FIS systems was chosen as an example. Figure 5.1 illustrates the rule viewer of the related FIS to social merit for one of the suppliers. Each rule is a row of plots and each column is a variable (S. R and, W. S & L. H, and Social Affinity Index) in Figure 5.1. The input values can be varied by moving the red line and the FIS system gives the output value. As five membership functions are considered for inputs, the number of rules will be 25 (5^2) to have the output value (Güneri et al., 2011). After verifying the rules, it was clear that the output value (Social Affinity Index) increases similarly to the results obtained from the input values (S. R and W. S &L. H).

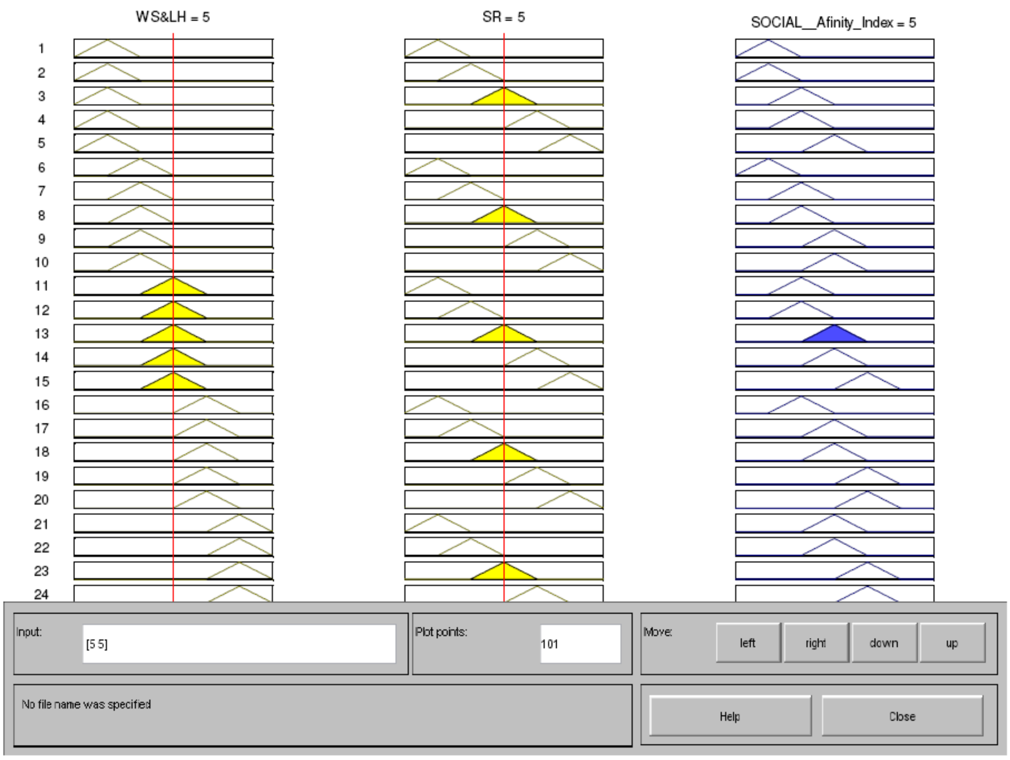


Figure 5.1: The rule viewer for one of the suppliers in the proposed modular FIS system.

Also getting the output surface from MATLAB Software for the aforesaid FIS system, it is found that the Social Affinity Index increases by increasing the amount of SR and W.S & L.H as seen in Figure 5.2

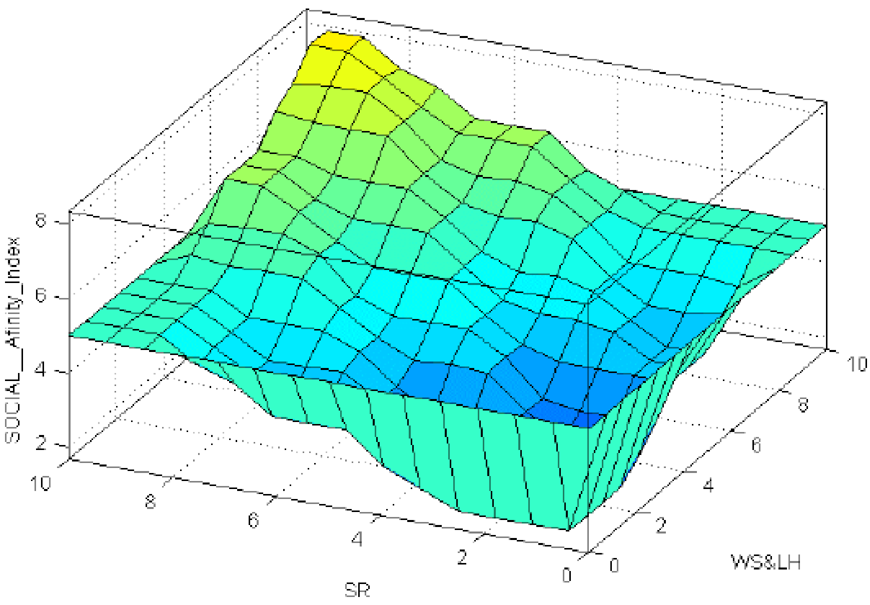


Figure 5.2: The output surface for one of the suppliers in the proposed modular FIS method.

The modular FIS system outputs as explained in section 4.2.3 identify the sustainability affinity indices as presented in Table 5.5. The sustainability affinity indices are obtained based on decision makers' preference (Table 5.1 and Table 5.2) and the modular FIS system performance. The amount of affinity index shows the supplier's capability for the related criteria (economic, environmental, and social) in comparison with others. For example, for the first supplier, the environmental affinity index is more than the economic and social affinity indices [0.6728>0.5179, 0.4]. In fact, the environmental performance of the first supplier is better than those of the other criteria groups according to decision makings' preferences. It may be mentioned that the evaluation of suppliers in this stage is excluding the relative importance issue of performance indicators. The calculations for getting the affinity indices are shown in Appendix-E in "Getting the sustainability affinity indices" part. It is noteworthy that the maximum value of affinity indices is 8.334 based on the maximum value of the suppliers' performance rates as seen in Table 4.2.

Table 5.5: Sustainability affinity indices of the modular FIS system for suppliers in the first test bed

		Affinity Indices		
		Economic	Environmental	Social
Suppliers	1	0.5179	0.6728	0.4
	2	0.4822	0.7273	0.3274
	3	0.6	0.6	0.5273
	4	0.4822	0.4728	0.2001
	5	0.3995	0.4728	0.3274
	6	0.3999	0.4728	0.3274
	7	0.2004	0.2001	0.2727
	8	0.2821	0.2727	0.3274

It is noteworthy that a sample result provided by MATLAB programming is shown in Appendix-H. To consider the relative importance of performance indicators for this test bed, the arrays of Table 5.1 is multiplied with the arrays of Table 5.2 according to equation (4.9) and then aggregated based on equation (4.3). Then, the calculated fuzzy matrix is deffuzified according to equation (4.11). These calculations are shown in Appendix-E in “Process on the weights” part. Finally, the weight ratio of paired criteria is obtained based on equation (4.12) as shown in Table 5.6. This process is shown in Appendix-F in “Calculate the weight restrictions” part.

Table 5.6: The lower and upper bounds for weight ratio of the proposed FIS-DEA method for paired criteria in the first test bed

		Economic/ Environmental	Environmental/ Social	Economic / social
Criteria bounds	Lower Bound	0.8867	1.4500	1.5313
	Upper Bound	1.2983	1.7959	2.3316

The results in Table 5.6 are considered as weight restrictions for DEA technique according to equation (2.14). Also, the arrays of Table 5.5 were fed in to the DEA technique as output variables according to equation (4.14). Considering one dummy input, the DEA is executed by Lingo software (see Appendix-F) and the supplier ranking result was obtained as shown in Table 5.7. The results of “Getting the sustainability affinity indices” and “Calculate the weight restrictions” parts from MATLAB programming are passed into the Lingo programming as seen in Appendix-F to get the suppliers’ ranking and efficiency scores.

Table 5.7: Relative efficiency scores and ranking of suppliers of the proposed FIS-DEA in the first test bed

	Suppliers							
	1	2	3	4	5	6	7	8
Efficiency scores	0.9502805	0.9379487	1.00000	0.7107682	.7079947	0.7082435	0.3730520	0.4969135
Ranking	2	3	1	4	6	5	8	7

Going through Table 5.5, the amount of social affinity index for the third supplier is the largest one. The averaging of economic and environmental affinity indices of this supplier is also more than those of the other suppliers. That is why; the best supplier in this test bed is supplier 3 due to its total capability in the criteria groups considering the relative importance weights as shown in Table 5.7. It can been clearly seen from Table 5.7 that the first and second suppliers have been assigned the second and third scores due to their affinity indices as shown in Table 5.5.

The optimal output multipliers of the DEA in the proposed FIS-DEA method are shown in Table 5.8. As seen, all of the multipliers are assigned non zero values because of considering the decision makers’ preference (Table 5.1 and Table 5.2) to incorporate the relative importance of criteria and sub-criteria as additional constraints (Table 4.3) in the proposed FIS-DEA method. However, in conventional DEA model the multipliers may be assigned to be zero illogically. Furthermore, the obtained weight ratios (Table 5.8) satisfy the desired conditions in Table 5.6. For example, the ratio of economic and environmental criteria for criteria in the first test bed for supplier 1 equals to $0.6219692/0.7014427 = 0.8867$ which is in the obtained range $0.8867 \leq 0.8867 \leq 1.2983$ according to Table 5.6. So, the results show that the weight restrictions have been implemented properly in the proposed method.

Table 5.8: The optimal multipliers of the proposed FIS-DEA method for criteria in the first test bed

		Criteria		
		Economic	Environmental	Social
Suppliers	1	0.6219692	0.7014427	0.3905800
	2	0.6219692	0.7014427	0.3905800
	3	0.6219692	0.7014427	0.3905800
	4	0.7344644	0.5889475	0.3905800
	5	0.6219692	0.7014427	0.3905800
	6	0.6219692	0.7014427	0.3905800
	7	0.7207627	0.5889475	0.4061707
	8	0.7207627	0.5889475	0.4061707

5.1.2 Piloting the Second Test Bed for Malaysian Company

In this section, another test bed from a company namely Proton which is located in Malaysia and produces a variety of cars is considered to show the application of the proposed method. The chosen company was established in the early 1980s. Its staff strength is above 20,000, with a plant capacity of production over 250,000 vehicles per annum. It has a market reach of over half a dozen countries including Singapore, Indonesia, Brunei, Fiji, Nepal, Sri Lanka, and Pakistan. To maintain or increase the market shares in those countries and to reach out to other countries, given the completion in those markets are intense, the Proton Company needs to select the most competent suppliers to get the right materials for its products. As Malaysia has a vision to be a developed country in near future, all aspects of this research for sustainable supplier selection including the respective criteria are quite significant. Malaysia is very much concerned about the environment and sustained relationships with suppliers for the Proton cars' parts. So the supplier selection decision from a sustainable point of view would be a key part to improve its business activities in competitive markets. The procurement team of two decision makers (DM1 and DM2) from department of quality and department of purchasing contributed in decision process. The derived data are shown in Table 5.9 and Table 5.10, respectively. As shown in Table 5.9, 12 performance indicators with different weights are implemented in three criteria groups.

Table 5.9: Decision makers' opinions for criteria weights in the second test bed

		DM1	DM2
Criteria	Economic	EI(0.67, 0.84, 1.0)	EI(0.67, 0.84, 1.0)
	Environmental	MI(0.34, 0.5, 0.67)	SI(0.5, 0.67, 0.84)
	Social	LMI(0.167,0.34, 0.5)	LMI(0.167,0.34, 0.5)

Table 5.10: Decision makers' opinions for sub-criteria weights in the second test bed

		DM1	DM2
Sub criteria	Cost	EI(0.67, 0.84, 1.0)	EI(0.67, 0.84, 1.0)
	Delivery on time	SI(0.5, 0.67, 0.84)	EI(0.67, 0.84, 1.0)
	Quality	EI(0.67, 0.84, 1.0)	EI(0.67, 0.84, 1.0)
	T. C	MI(0.34, 0.5, 0.67)	SI(0.5, 0.67, 0.84)
	F. C	MI(0.34, 0.5, 0.67)	MI(0.34, 0.5, 0.67)
	Flexibility	SI(0.5, 0.67, 0.84)	MI(0.34, 0.5, 0.67)
	O& C	MI(0.34, 0.5, 0.67)	SI(0.5, 0.67, 0.84)
	Service	SI(0.5, 0.67, 0.84)	SI(0.5, 0.67, 0.84)
	E. C	LMI(0.167,0.34, 0.5)	MI(0.34, 0.5, 0.67)
	E. M. S	MI(0.34, 0.5, 0.67)	SI(0.5, 0.67, 0.84)
	S. R	LMI(0.167,0.34, 0.5)	LMI(0.167,0.34, 0.5)
	W. S & L. H	LMI(0.167,0.34, 0.5)	MI(0.34, 0.5, 0.67)

The number of candidate suppliers in the test bed was 6. Also, decision makers' preferences about suppliers' performance with respect to performance indicators are shown in Table 5.11.

Table 5.11: Decision makers' opinions on suppliers' performance in the second test bed

			Suppliers					
Sub criteria		**DMs**	1	2	3	4	5	6
	Cost	DM1:	EP	EP	SP	MP	LMP	LMP
		DM2:	EP	EP	SP	MP	LMP	MP
	Delivery on time	DM1:	EP	MP	MP	SP	LMP	MP
		DM2:	EP	SP	MP	MP	MP	WP
	Quality	DM1:	EP	EP	SP	EP	LMP	MP
		DM2:	EP	EP	SP	SP	MP	LMP
	T. C	DM1:	SP	SP	MP	SP	MP	LMP
		DM2:	EP	MP	MP	LMP	LMP	WP
	F. C	DM1:	SP	MP	EP	LMP	LMP	LMP
		DM2:	SP	MP	LMP	LMP	WP	WP
	Flexibility	DM1:	SP	SP	LMP	MP	LMP	WP
		DM2:	MP	MP	LMP	LMP	LMP	WP
	O& C	DM1:	SP	MP	MP	SP	MP	MP
		DM2:	SP	MP	MP	LMP	LMP	WP
	Service	DM1:	EP	EP	SP	EP	WP	LMP
		DM2:	EP	SP	SP	MP	LMP	LMP
	E. C	DM1	SP	LMP	MP	MP	MP	LMP
		DM2	SP	MP	LMP	LMP	WP	WP
	E. M. S	DM1	EP	SP	MP	EP	MP	WP
		DM2	EP	SP	MP	MP	LMP	LMP
	S. R	DM1	MP	LMP	MP	LMP	LMP	WP
		DM2	MP	LMP	LMP	LMP	WP	WP
	W. S & L. H	DM1	MP	SP	SP	MP	MP	WP
		DM2	SP	LMP	MP	LMP	WP	WP

Notes: Technological Capability= T.C; Financial Capability= F.C; Organization & Control= O&C; Environmental Competencies=E.C; Environmental Management System= E.M.S; Social Responsibility=S.R; Work Safety & Labor Health=W.S&L.H

Table 5.11 as decision makers' preference about suppliers' performance is considered as matrix arrays in equation (4.1) and aggregated according to equation (4.2) and equation (4.3) as mentioned in section 4.2.2.1. Then, similar to the test bed 1, the obtained FD matrix (4.5) is defuzzified according to COA method as shown in Table 5.12. The arrays of Table 5.12 is passed to the modular FIS system as explained in section 4.2.3 to get the sustainability affinity indices as presented in Table 5.13.

Table 5.12: Prepared inputs for the modular FIS system in the second test bed

		Suppliers					
		1	**2**	**3**	**4**	**5**	**6**
Sub criteria	Cost	8.3333	8.3333	6.6667	5	3.3333	4.1667
	Delivery on time	8.3333	5.8333	5	5.8333	4.1667	3.3333
	Quality	8.3333	8.3333	6.6667	7.5	4.1667	4.1667
	T. C	7.5	5.8333	5	5	4.1667	2.5
	F. C	6.6667	5	5.8333	3.3333	2.5	2.5
	Flexibility	5.8333	5.8333	3.3333	4.1667	3.3333	1.6667
	O& C	6.6667	5	5	5	4.1667	3.3333
	Service	8.3333	7.5	6.6667	6.6667	2.5	3.3333
	E. C	6.6667	4.1667	4.1667	4.1667	3.3333	2.5
	E. M. S	8.3333	6.6667	5	6.6667	4.1667	2.5
	S. R	5	3.3333	4.1667	3.3333	2.5	1.6667
	W. S & L. H	5.8333	5	5.8333	4.1667	3.3333	1.6667

Similar to the first test bed, all of the necessary calculations are done by MATLAB programming as shown in Appendix-E.

Table 5.13: Sustainability affinity indices of the modular FIS system for suppliers in the second test bed

		Affinity Indices		
		Economic	Environmental	Social
Suppliers	1	0.7002	0.8001	0.6
	2	0.6005	0.6	0.4
	3	0.4999	0.5	0.5
	4	0.4	0.6	0.3999
	5	0.3	0.3999	0.3
	6	0.2008	0.3	0.2001

To consider the relative importance of indicators for this test bed, the arrays of Table 5.9 is multiplied with the arrays of Table 5.10 according to equation (4.9) and aggregated based on equation (4.3). Then, the calculated fuzzy matrix is deffuzified according to equation (4.11). Finally, the weight ratio of paired criteria is obtained based on equation (4.12) as shown in Table 5.14.

Table 5.14: The lower and upper bounds of weight ratio of the proposed FIS-DEA method for paired criteria in the second test bed

		Economic/ Environmental	Environmental/ Social	Economic / social
Criteria bounds	Lower Bound	1.4688	1.7500	3.8015
	Upper Bound	2.4643	2.5882	4.3125

The results in Table 5.14 are considered as weight restrictions for DEA technique according to equation (2.14). Also, the arrays of Table 5.13 are fed in to the DEA technique as output variables according to equation (4.14). Considering one dummy input, the DEA is executed by Lingo software (see Appendix-F) and the supplier ranking result is obtained as shown in Table 5.15. The results from MATLAB programming are passed into the Lingo programming as seen in Appendix-F to get the suppliers' ranking and efficiency scores.

Table 5.15: Relative efficiency scores and ranking of suppliers for the proposed FIS-DEA method in the second test bed

	Suppliers					
	1	2	3	4	5	6
Efficiency scores	1.000000	0.8015295	0.6987777	0.6513518	0.4642120	0.3262743
Ranking	1	2	3	4	5	6

Table 5.15 shows the efficiency scores and ranking results for the suppliers based on affinity indices considering the relative importance of indicators.

The optimal output multipliers of the DEA in the proposed FIS-DEA method are shown in Table 5.16. As seen similar to the first test bed, all of the multipliers are assigned non zero values because of considering the decision makers' preference (Table 5.9 and Table 5.10) to incorporate the relative importance of criteria and sub-criteria as additional constraints (Table 4.3) in the proposed method. Furthermore, the obtained weight ratios (Table 5.16) satisfy the desired conditions in Table 5.14. For example the ratio of environmental and social criteria for criteria in the first test bed for supplier 6 equals to $0.48534780/1875257 = 2.58817$ which is in the obtained range $1.75 \leq 2.58817 \leq 2.5882$ according to Table 5.16. So, the results show that the weight restrictions have been implemented properly in the proposed method.

Table 5.16: The optimal multipliers of the proposed FIS-DEA method for criteria in the second test bed

		Criteria		
		Economic	**Environmental**	**Social**
Suppliers	1	0.8087045	0.4014869	0.1875257
	2	0.8087045	0.4014869	0.1875257
	3	0.8087045	0.4014869	0.1875257
	4	0.7128789	0.4853478	0.1875257
	5	0.7128789	0.4853478	0.1875257
	6	0.7128789	0.4853478	0.1875257

In this way, the applicability and feasibility of the proposed FIS-DEA method were tested and presented through two test beds in this section.

It is noteworthy that a sample result provided by MATLAB programming is shown in Appendix-I.

5.2 Validation of the Proposed FIS-DEA Method

To evaluate the proposed FIS-DEA method, the existing FIS-based supplier selection method is compared with the proposed method through the two test beds. The performance of the proposed FIS-DEA method is assessed by the error measurement criteria.

These test beds are fed into the FIS-based supplier selection method to get the ranking results. To calculate the input variables for the test beds, the fuzzy aggregated supplier performances in equation (4.5) is multiplied by the fuzzy aggregated importance weight of each sub-criterion in equation (4.16). Then, the obtained fuzzy numbers were defuzzified to the desired crisp numbers as input variables for the FIS systems in the first stage to test bed 1 and test bed 2 as shown in Table 5.17 and Table 5.18, respectively.

Table 5.17: Prepared inputs for the FIS-based supplier selection method in the first test bed

		Suppliers							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Sub criteria	Cost	7.4444	5.7778	8	6.3333	5.2222	5.7778	3.5556	4.6667
	Delivery on time	5.5185	5.037	5.5185	4.5556	5.037	5.037	2.1481	3.5926
	Quality	6.4444	5.4074	6.963	5.4074	4.8889	4.8889	3.3333	3.3333
	T. C	4.7037	3.8889	5.5185	4.2963	3.4815	3.8889	2.2593	2.6667
	F. C	2.8889	2.2963	2.8889	2.5926	2.5926	3.1852	2.2963	1.4074
	Flexibility	2	1.7778	2.2222	1.3333	1.5556	1.1111	1.3333	0.8889
	O& C	3.2222	2.5556	3.2222	2.8889	2.5556	2.5556	1.5556	1.8889
	Service	3.5556	2.8889	4.8889	3.5556	2.8889	3.5556	1.5556	2.5556
	E. C	4.6667	5.037	4.6667	2.8148	2.8148	2.8148	1.7037	1.3333
	E. M. S	4.6667	5.1111	4.2222	3.3333	3.3333	3.3333	2.8889	1.5556
	S. R	2	1.7037	2.5926	1.7037	1.7037	1.1111	1.7037	1.7037
	W. S & L. H	1.5556	1.3333	2	1.3333	1.3333	0.8889	1.3333	1.1111

Table 5.18: Prepared inputs for the FIS-based supplier selection method in the second test bed

		Suppliers					
		1	**2**	**3**	**4**	**5**	**6**
Sub criteria	Cost	8.5556	8.5556	5.2222	6.8889	3.5556	4.3889
	Delivery on time	7.7222	5.4722	5.4722	4.7222	3.9722	3.2222
	Quality	8.5556	8.5556	7.7222	6.8889	4.3889	4.3889
	T. C	5.4722	4.3056	3.7222	3.7222	3.1389	1.9722
	F. C	4.2222	3.2222	2.2222	3.7222	1.7222	1.7222
	Flexibility	4.3056	4.3056	3.1389	2.5556	2.5556	1.3889
	O& C	4.8889	3.7222	3.7222	3.7222	3.1389	2.5556
	Service	6.8889	6.2222	5.5556	5.5556	2.2222	2.8889
	E. C	3.5556	2.3056	2.3056	2.3056	1.8889	1.4722
	E. M. S	6.0556	4.8889	4.8889	3.7222	3.1389	1.9722
	S. R	2.2222	1.5556	1.5556	1.8889	1.2222	0.8889
	W. S & L. H	3.1389	2.7222	2.3056	3.1389	1.8889	1.0556

The arrays of aforementioned matrices were passed to the FIS-based supplier selection method to get outputs in the first stage. Then, the fuzzy weight of economic criterion ($\tilde{W}C11$) was defuzzified to crisp number and multiplied by its related output value in the second stage. Also, the average between the weights of environmental ($\tilde{W}C21$) and social criteria ($\tilde{W}C31$) was defuzzified to crisp number and multiplied by its related output value in the second stage (see Figure 4.8).

Finally the ranking results of the FIS-based supplier selection method for the first and second test bed are shown in Table 5.19 and Table 5.20, respectively.

Table 5.19: Relative efficiency scores and ranking of suppliers of the FIS-based supplier selection method in the first test bed

	Suppliers							
	1	2	3	4	5	6	7	8
Efficiency scores	66.1555	65.8601	74.317	47.0995	38.0398	43.8854	30.8232	30.8306
Ranking	2	3	1	4	6	5	8	7

According to Table 5.7 and Table 5.19 for the first test bed and Table 5.15 and Table 5.20 for the second test bed, the ranking results for the proposed method and FIS-based method are the same. This finding shows that the proposed method is valid and working well. It is worthy to note that, there are some advantages for the proposed FIS-DEA method in comparison with the existing FIS-based supplier selection method. The proposed FIS-DEA method can overcome the shortcomings of conventional DEA technique which will be explained in section 5.3. Also, the optimal multipliers obtained from the proposed method are additional information besides the supplier ranking results in comparison with the existing FIS-based.

Table 5.20: Relative efficiency scores and ranking of suppliers of the FIS-based supplier selection method in the second test bed

	Suppliers					
	1	2	3	4	5	6
Efficiency scores	91.1819	77.0043	71.9372	71.087	36.6024	30.5315
Ranking	1	2	3	4	5	6

To clarify the efficiency comparisons, they are shown graphically in Figure 5.3 and Figure 5.4. It must be mentioned that in these Figures the efficiency scores have been normalized by dividing by 100 to obtain desired range between zero and one.

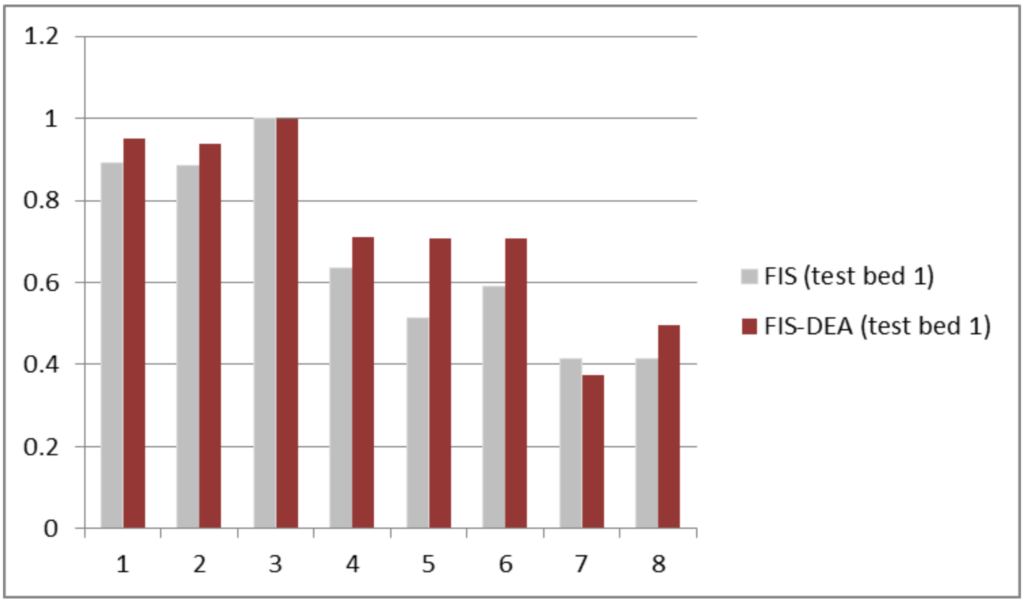


Figure 5.3: Comparing the efficiency scores for the proposed FIS-DEA and FIS-based method in the first test bed.

As seen in Figure 5.3, the sequence of supplier ranking is the same for the both FIS-DEA and FIS-based methods in the first test bed. It can be shown for the second test bed in Figure 5.4.

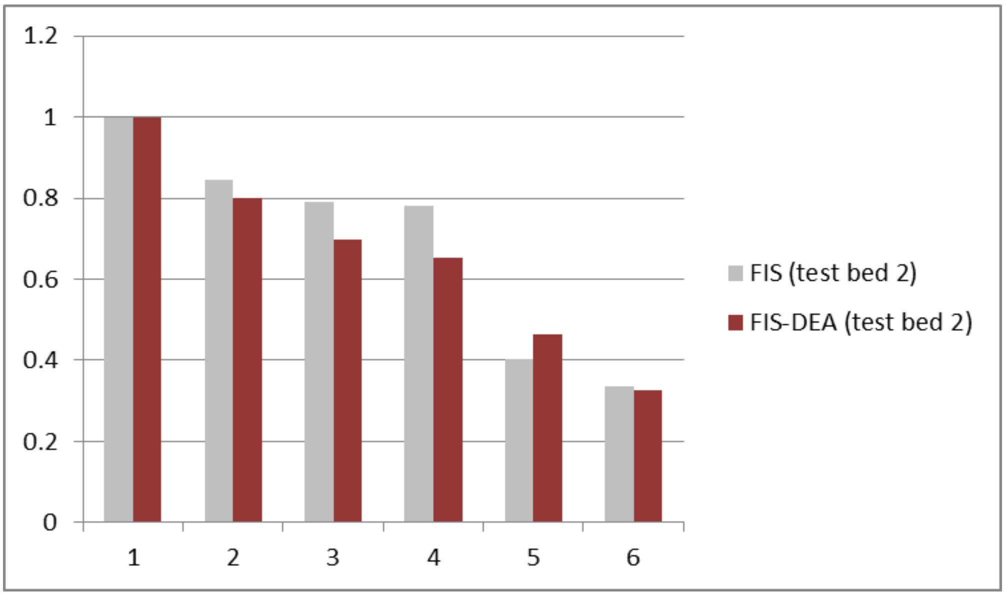


Figure 5.4: Comparing the efficiency scores for the proposed FIS-DEA and FIS-based method in the second test bed.

Although the supplier ranking results are the same for the proposed FIS-DEA method and existing FIS-based method, the amounts of score ranking are not the same and there should be some errors. So, the amounts of errors would be measured to show the validity. To obtain the error measurement criteria, the ranking results from the existing FIS-based supplier selection method are considered as experimental value and the ranking results from the proposed method are considered as predicted value (Vahdani et al., 2012) in the error measurement formulas which has been mentioned briefly in Chapter 3. It is noteworthy that the efficiency scores must be normalized to obtain the errors correctly. The obtained errors for the first and second test beds are presented in Table 5.21. Graphical charts of these error measurements are shown in Figure 5.5 and Figure 5.6.

Table 5.21: Error measurement criteria of the proposed FIS-DEA method and the FIS-based method

	Error measurement criteria		
	MAE	MSE	RMSE
The first test bed	0.0783	0.0091	0.0955
The second test bed	0.0555	0.0051	0.0712

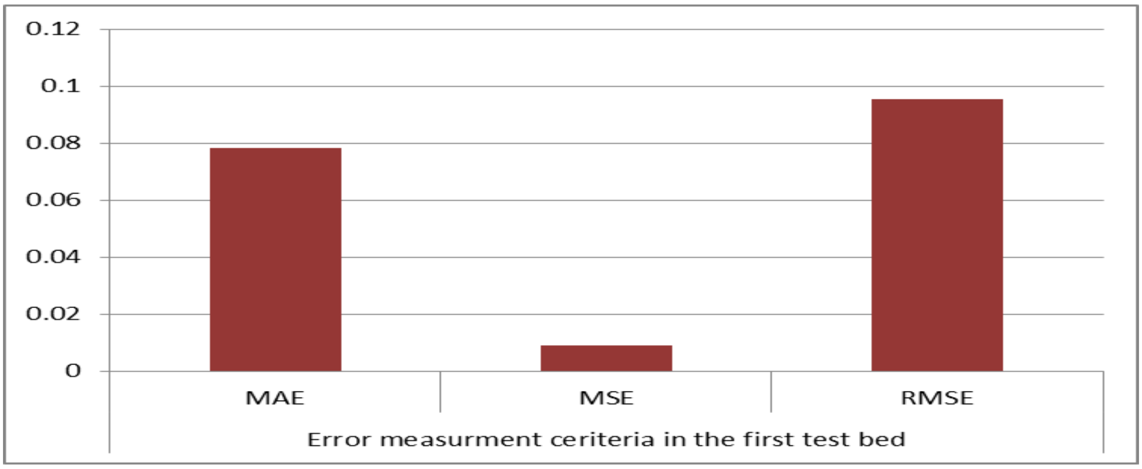


Figure 5.5: Error measurement criteria for the proposed FIS-DEA and FIS-based method in the first test bed.

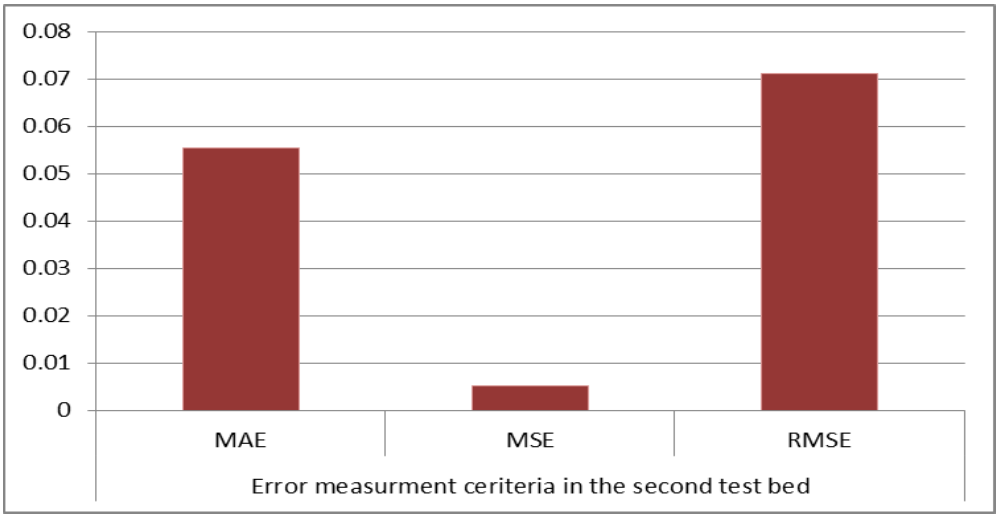


Figure 5.6: Error measurement criteria for the proposed FIS-DEA and FIS-based method in the second test bed.

As seen in Table 5.21, the amount of all error measurement criteria is very small and this shows the validation of the proposed method. Comparing the ranking results of the proposed method with the FIS-based method through the two test beds shows that the proposed method comes up with the FIS-based method.

5.3 Additional Discussion on Research Contributions

This section intends to examine the effects of the contributions of this thesis on the supplier ranking process. This work has focused to overcome the shortcomings of DEA. In addition the majority of the supplier selection method is designed based on AHP approach as referred in section 2.2.2. So considering the shortcomings of DEA and AHP approaches as mentioned in Chapter 2, some additional discussion on the findings of this research is included in this section through the two test beds to show the advantages of the proposed method.

In the conventional DEA approach, the input and output variables must be crisp data. So, to pass the data of test beds into the stand-alone DEA technique (equation

4.14) these data must be transferred into the fuzzy environment and prepared. So, the data of Table 5.4 and Table 5.12 are normalized and they are used as inputs for the first and second test beds, respectively are fed into the DEA approach to get the ranking results. The 12 indicators which implemented in the two test beds are considered as output variables for the DEA technique with the consideration of one dummy input. The results of the two executions using Lingo programming (see Appendix-G) are shown as Table 5.22 and Table 5.23.

Table 5.22: Relative efficiency scores and ranking of suppliers using DEA method in the first test bed

	Suppliers							
	1	2	3	4	5	6	7	8
Efficiency scores	1.714206	1.857010	1.714206	1.249919	1.000000	1.000000	1.000000	1.000000
Ranking	2	1	2	3	4	4	4	4

Table 5.23: Relative efficiency scores and ranking of suppliers using DEA method in the second test bed

	Suppliers					
	1	2	3	4	5	6
Efficiency scores	2.000000	1.666667	1.750000	1.000000	0.8333333	0.8333333
Ranking	1	3	2	4	5	5

According to Table 5.7 and Table 5.22 for the first test bed and Table 5.15 and Table 5.23 for the second test bed, the ranking results for the proposed FIS-DEA method and DEA method are not the same. For example, from Table 5.22, it can be clearly seen that the ranking of third supplier in the first test bed for DEA method is 2 while for the proposed FIS-DEA is 1 (see Table 5.7). Based on sustainability affinity indices which discussed in section 5.1.1, the third supplier must be the best supplier in this test bed due to its high economic and social affinity indices as shown in Table 5.5. So, this contradiction shows the shortcoming of DEA method. This contradiction also can be presented graphically in Figure 5.7 and Figure 5.8 for the first and second test beds, respectively. In this Figures the efficiency scores have been also normalized.

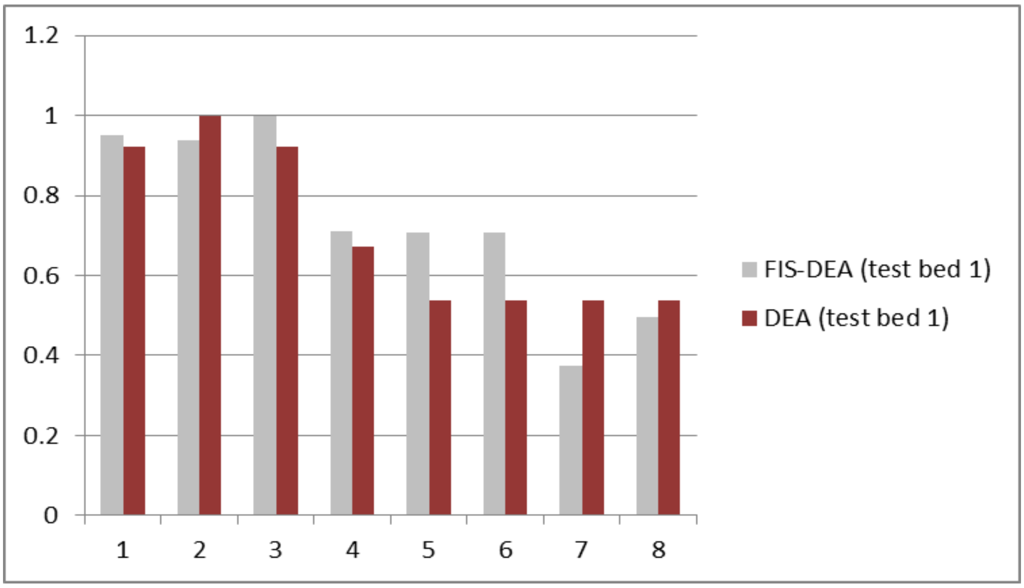


Figure 5.7: Comparing the efficiency scores for the proposed FIS-DEA and DEA method in the first test bed.

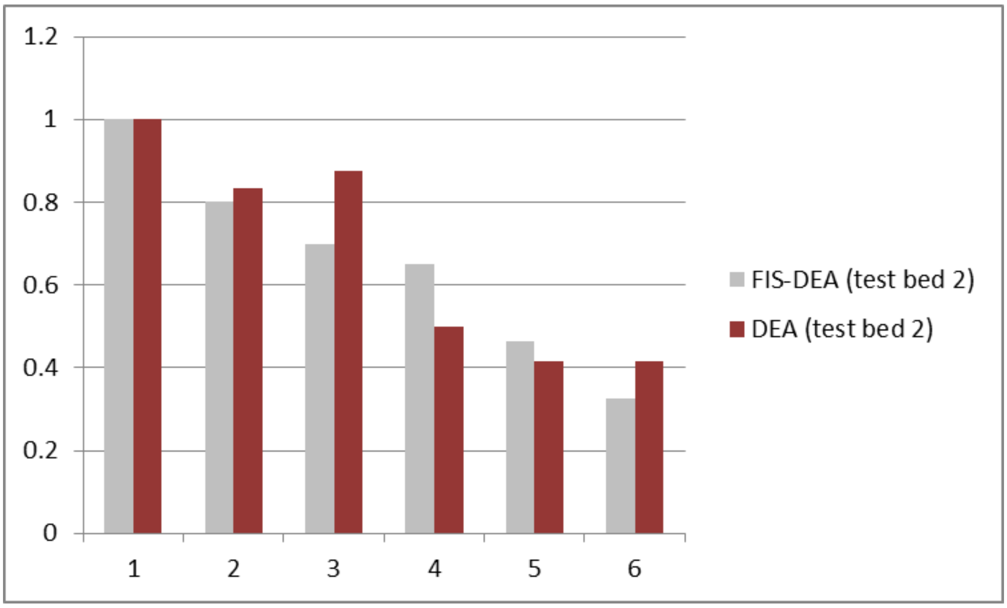


Figure 5.8: Comparing the efficiency scores for the proposed FIS-DEA and DEA method in the second test bed.

The optimal output multipliers of the conventional DEA for the first and second test beds are shown in Table 5.24 and Table 5.25, respectively using Lingo programming (see Appendix-G). Having a look at these Tables (the weights of inputs and outputs); it is found that a zero weights to some inputs and/or outputs have been assigned. So, an efficient supplier may become so by assigning a zero weight to the inputs and/or outputs on which its performance is worst. This might not be acceptable by decision makers as well as by the analyst, who after spending time in a careful selection of inputs and outputs sees some of them being completely neglected by suppliers (R.F. Saen, 2010).

In such circumstances to achieve a reasonable level of discrimination power of DEA there is a suggestion. A suggested "rule of thumb" is that, the number of decision making units (suppliers) must be at least $2 \times J \times L$ (*L* is number of inputs and *J* is the number of outputs (Dyson et al., 2001). So, for the two test beds with 1 input and 12 outputs, the number of candidate suppliers must be at least 24. It means that the stand-alone DEA cannot be applied in the supplier selection problem for the two test beds. In other words, the stand-alone DEA method cannot be an appropriate tool for supplier selection problem in manufacturing and real-life problems.

Table 5.24: The optimal multipliers of the conventional DEA approach for criteria in the first test bed

		Suppliers							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Sub criteria	Cost	0	0	0	0	0	1.18175	0	0
	Delivery on time	0	0	0	0	0	0	0	0
	Quality	0	0	0	0	0	0	0	0
	T. C	0	0	0	0	0	0	0	0
	F. C	0	0	0	1.62496	0	0	0	0
	Flexibility	0	0	0	0	2.16684	0	0	0
	O& C	0	0	0	0	0	0	0	0
	Service	0	0	0	0	0	0	0	0
	E. C	1.85701	1.857010	1.857010	0	0	0	0	0
	E. M. S	0	0	0	0	0	0	0	0
	S. R	0	0	0	0	0	0	2.60010	0
	W. S & L. H	0	0	0	0	0	0		2.60014

Considering the sustainability issues in supplier selection problem makes it more complicated in case of increasing the number of performance indicators. Because, the number of performance criteria gets more if sustainability issues are considered. As it mentioned earlier, the number of weigh restrictions depends on the number of performance indicators. For example, if the number of indicators would be n, the number of weight restrictions should be $n \times (n-1)/2$. For the two test beds, the number of performance indicators is 12. So, the number of weight restrictions is equal to 66

$(=12\times(12-1)/2)$. It is obvious that execution of DEA model with consideration of these 66 constraints is very time-consuming and almost infeasible. So, this would be shown as a significant role of the FIS approach in the proposed method to reduce the capacity of the computations and overcome the shortcomings of the DEA.

Table 5.25: The optimal multipliers of the conventional DEA approach for criteria in the second test bed

		Suppliers					
		1	**2**	**3**	**4**	**5**	**6**
Sub criteria	Cost	0	1.667	0	0	0	1.667
	Delivery on time	0	0	0	0	0	0
	Quality	0	0	0	1.111	0	0
	T. C	0	0	0	0	0	0
	F. C	2.500	0	2.500	0	0	0
	Flexibility	0	0	0	0	0	0
	O & C	0	0	0	0	0	0
	Service	0	0	0	0	0	0
	E. C	0	0	0	0	0	0
	E. M. S	0	0	0	0	0	0
	S. R	0	0	0	0	0	0
	W. S & L. H	0	0	0	0	0	0

Adding the weight restrictions in the stand-alone DEA technique makes this more discriminating in assessing the performance of decision making units (suppliers) (Dyson et al., 2001). So, the assurance region model of DEA technique (DEA-AR) has been taken into the account for the proposed method. On the other hand, to show the effects of the weight restrictions in the supplier selection problem, the weight restrictions of the proposed method are omitted. In fact, the FIS is integrated with traditional DEA (not DEA-AR) and the obtained results on this scenario were analyzed and compared with the proposed method as below.

The arrays of Table 5.5 for the first test bed and the arrays of Table 5.13 for the second test bed are fed in to the DEA technique as output variables according to equation (4.14). Considering one dummy input, the DEA is executed by Lingo software and the supplier ranking results for two test beds are obtained as shown in Table 5.26 and Table 5.27, respectively.

Table 5.26: Relative efficiency scores and ranking for suppliers of the FIS-DEA without weight constraints in the first test bed

	Suppliers							
	1	2	3	4	5	6	7	8
Efficiency	1.000000	1.081005	1.318250	0.9310678	0.8185000	0.8185000	0.6817500	0.8185000
Ranking	3	2	1	4	5	5	6	5

Table 5.27: Relative efficiency scores and ranking for suppliers of the FIS-DEA method without weight constraints in the second test bed.

	Suppliers					
	1	2	3	4	5	6
Efficiency	1.000000	0.8576121	0.8333333	0.7499063	0.5000000	0.3749531
Ranking	1	2	3	4	5	6

According to Table 5.7 and Table 5.26 for the first test bed, the ranking results for the proposed FIS-DEA method considering weight restrictions and FIS-DEA without that are not the same. For example from Table 5.26, it can be seen that for the three suppliers (5, 6, and 8) the amount of efficiency scores are the same while their sustainability affinity indices are different (see Table 5.5). This contradiction also can be presented graphically in a Figure 5.9. In addition, the optimal output multipliers of the FIS- DEA without considering weight restrictions are shown in Table 5.28. As seen in this table, some zero weights have been assigned to some outputs and this is not logical as mentioned before.

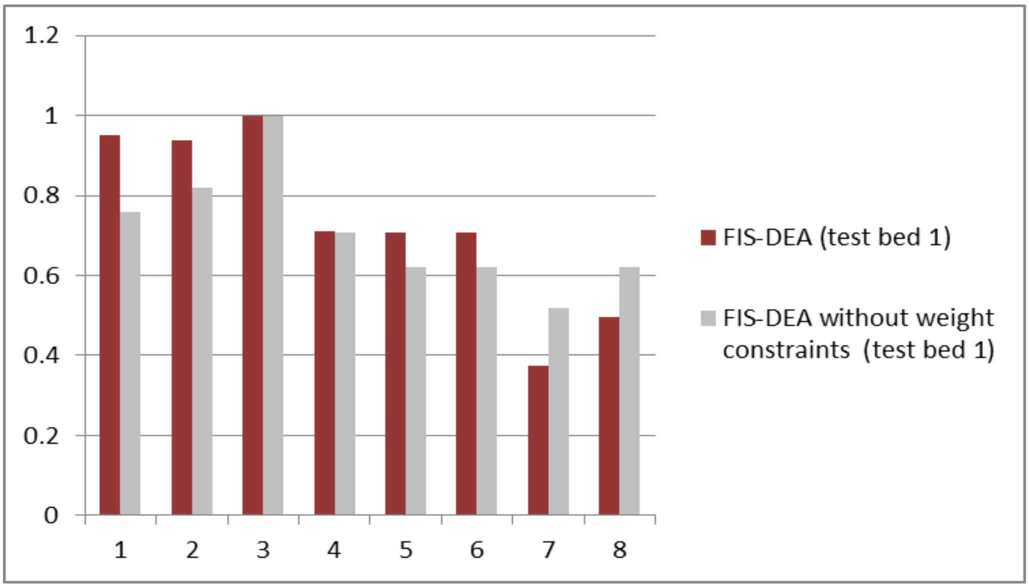


Figure 5.9: Comparing the efficiency scores for the proposed method and FIS-DEA without weight restrictions in the first test bed.

About the second test bed, Table 5.15 and Table 5.27 show the ranking results for the proposed FIS-DEA method and FIS-DEA without considering weight restrictions, respectively. However, the ranking results are the same but again; some zero weights have been assigned to some outputs according to Table 5.29. The efficiency scores of the proposed method and the FIS-DEA without weight constraints are shown graphically in Figure 5.10.

The results of the FIS-DEA without weight restrictions for the two test beds indicate, this method not only is unable to overcome the shortcomings of the DEA but also its ranking result is not correct.

Table 5.28: The optimal multipliers of the FIS-DEA method without weight constraints for criteria in the first test bed

		Criteria		
		Economic	Environmental	Social
Suppliers	1	0	1.486326	0
	2	0	1.486326	0
	3	0	0	2.500000
	4	1.930875	0	0
	5	0	0	2.500000
	6	0	0	2.500000
	7	0	0	2.500000
	8	0	0	2.500000

Table 5.29: The optimal multipliers of the FIS-DEA method without weight constraints for criteria in the second test bed

		Criteria		
		Economic	Environmental	Social
Suppliers	1	0	1.249844	0
	2	1.428163	0	0
	3	0	0	1.666667
	4	0	1.249844	0
	5	0	0	1.666667
	6	0	1.249844	0

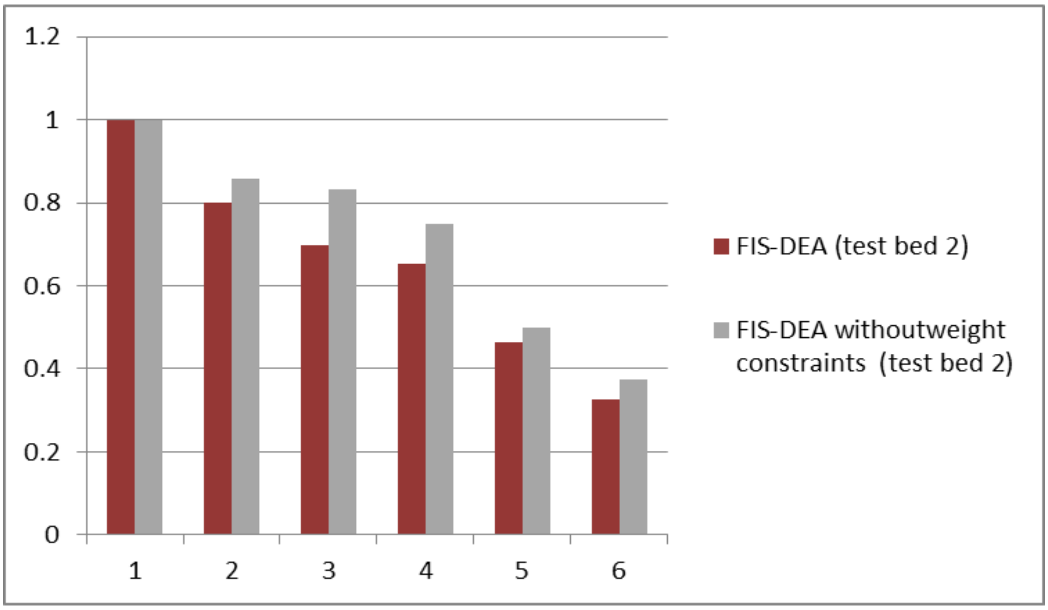


Figure 5.10: Comparing the efficiency scores for the proposed FIS-DEA method and FIS-DEA without weight restrictions in the second test bed.

To show the contribution of the proposed method in case of its open-ended characteristic, execution of AHP approach for the two test beds is verified in follow. In AHP, the number of pair wise comparisons for n performance indicators is $n \times (n-1)/2$ for each supplier. When the number n of performance indicators in a decision increases, the required number of pair wise comparisons also increase. As a result of too many questions and comparisons, it may cause evaluator's mental confusion, and thus easily results in inconsistent situations. For example, for the first test bed which includes 12 supplier selection sub-criteria and 8 candidate suppliers, the number of total comparisons is $8 \times 12 \times 11/2 = 528$. Also for the second test bed, the number of required pair wise comparisons would be $6 \times 12 \times 11/2 = 396$. It is obvious that execution of AHP with consideration of this huge number of constraints is very time-consuming and inconvenience as well as in terms of computational complexity.

The all aforementioned discussions in this section indicate that the proposed FIS-DEA method can be appropriate tool for sustainable supplier selection problem in manufacturing and real-life problems and the specific salient advantages of the proposed method are as follows:

- Applying the weight restrictions to assign none zero weights to inputs and/or outputs.
- To achieve a reasonable level of discrimination power of DEA.
- To reduce the capacity of the computations as compared with DEA.
- The suitable method to replace the AHP method for supplier selection problem.

CHAPTER 6

CONCLUSION AND FUTURE RESEARCH

Discussions on the main findings and various issues have been placed in the past chapters. The supplier selection specific problems and the proposed method were located and the necessary recommendations were placed. This chapter summarizes the findings of the research.

6.1 Summary of the Work

Overall, the objectives of this research are achieved. The research has been organized on the two existing views. One is what performance indicators should be used, and the other, what methods can be used to rank and select the best suppliers. In regard to the performance indicators, it has been focused on sustainability issues to improve supplier selection process and make it compatible to the present-day requirements. About methods, it has been focused on two current aspects- relative importance of the performance indicators and uncertainty - to expand the supplier selection literature. Appropriate decision making method is necessary to create a conceptual sustainable supplier selection model under uncertainty considering the relative importance of performance indicators. In this work, the relevant sustainability issues for supplier selection have been located, and the DEA technique and its shortcomings have been focused to develop the decision making methods under the uncertainties. This research developed a comprehensive supplier selection model for manufacturing. The proposed method is designed as open ended to adapt any number of supplier selection criteria and candidate suppliers for today's manufacturing suitable for small, medium and large enterprises.

6.2 Conclusions

The main conclusions of this research are as follows:

i. A comprehensive framework has been proposed for sustainable supplier selection by taking into account of the main economic, environmental, and social aspects. This framework can be used in manufacturing as well as service industries.

ii. An integrated FIS-DEA method for supplier selection has been developed by incorporating the sustainability issues in the selection process for manufacturing firms, where the sustainability is a significant concern.

iii. The proposed FIS-DEA method can be used for companies those are having problems in a supplier selection system when related information is imprecise. Also, incorporation of relative importance of performance indicators will provide added benefits to the decision model that support manufacturing or service firms in the supplier selection process.

iv. This robust model can be used for multi-criteria decision making problems with any number of suppliers and indicators. Matlab programming software can solve FIS-DEA model reliably.

v. Suppliers' ranking through the efficiency scores obtained under the proposed method is in agreement with the FIS method. This validates the acceptance of the proposed FIS-DEA method. The proposed FIS-DEA method can be for supplier selection considering sustainability aspects tin addition to the conventional economic or cost-based aspects.

The research expanded the knowledge in the supplier selection area and come up with the publications of ISI, SCOPUS, and other journal and conference papers (Appendix-J).

6.3 Further Research Direction

The research reported in this thesis is not definitely comprehensive for the area in question but is a step ahead to the researches worked by few other academics. The main contribution of this thesis is the development of the FIS-DEA integrated method for sustainable supplier selection. This work can be extended into the following areas/directions:

i. More concentration on sustainability issues in supplier selection in terms of performance indicators can be remained as a challenge.

ii. Further work can be done on the improvement of the proposed method for the multiple sourcing environments instead of only single sourcing. So, how to assign orders to the appropriate suppliers in the proposed FIS-DEA method can be a subject for future research.

iii. Further efforts may be done in executing the proposed method for real case supplier selection decision in manufacturing for the future.

iv. The systematic methods suggested in this research for supplier selection can be implemented to other types of decision making, such as supply chain evaluation, technology selection, and personnel selection.

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APPENDICES

Appendix-A: Questionnaires for data collection

A1.Relative importance of performance indicators being attached for supplier selection in manufacturing/assembling of company products

Please write down the name of the product(s) that are relevant to sustainable economic, environmental and social aspects: ………………………………………………………..

Please encircle on the box you find appropriate.

Main Criteria (indicators)	Importance being attached by the company					Sub-criteria (indicators)	Importance being attached by the company					
Sustainable Economic aspects	1	2	3	4	5	Economic aspects						
						Constant reduction of manufacturing cost or cost per unit load supply	0	1	2	3	4	5
						Delivery on time, potential for cycle time or lead time reduction	0	1	2	3	4	5
						Specified Quality, quality management system of supplier.	0	1	2	3	4	5
						Technological capability (manufacturing facilities and capabilities, productivity, innovation, knowledge workers, documentation)	0	1	2	3	4	5
						Financial capability (ability for further investment, return on investment (ROI), healthy net present value (NPV))	0	1	2	3	4	5
						Flexibility (variety in raw materials or components, ability to produce/supply under make-to-order or assemble-to-order environments, facility planning, etc.)	0	1	2	3	4	5
						Organization & control (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	0	1	2	3	4	5
						Services and communications with the supplier (able to provide after services on time, ensure reliability)	0	1	2	3	4	5
						Any other indicator you consider: please specify ………………………………..	0	1	2	3	4	5
Conserved/preserved Environmental aspects	1	2	3	4	5	Concern about preservation of environment						
						Attainment of sustainable environmental competencies	0	1	2	3	4	5
						Environmental management system (carry out environmental impact assessment (EIA) periodically, reporting to the customer, etc.	0	1	2	3	4	5
						Any other indicator you consider: please specify ………………………………..	0	1	2	3	4	5
Healthy/sound Social aspects	1	2	3	4	5	Ability to develop long-term relationships with customer						
						Social- responsibilities (following professional/engineering ethics, help building social institutions, not using child labor, etc.)	0	1	2	3	4	5
						Work safety & labor health	0	1	2	3	4	5
						Any other indicator you consider: please specify ………………………………..	0	1	2	3	4	5

Notes: Not Considered = (0); Weak Importance = (1); Low Moderate Importance = (2); Moderate Importance = (3); Strong Importance = (4); Extreme Importance = (5)

A2. A supplier’s performances for a specified product from sustainable point of view

Supplier Company name…

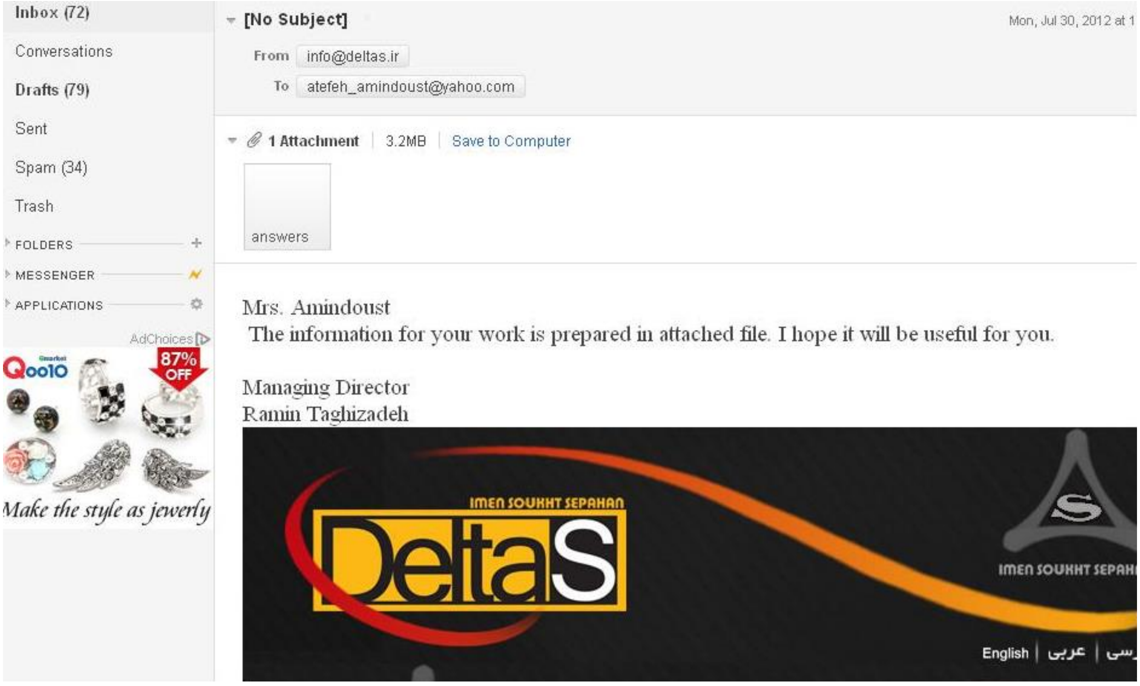
Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier’s performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers’ request, efficiency of engineering support, fulfilling customers’ special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

Appendix-B: Data collection for Test-bed 1 (Imen Soukht Sepahan Company)

Correspondence for data collection



Relative importance of attributes being attached for supplier selection in manufacturing/assembling of company products

Please write down the name of the product(s) that are relevant to sustainable economic, environmental and social aspects: ....Aluminium...alloy_3003........

Please encircle on the box you find appropriate.

Main Criteria (indicators)	Importance being attached by the company					Sub-criteria (indicators)	Importance being attached by the company					
Sustainable Economic aspects	1	2	3	4	5	Economic aspects						
						Constant reduction of manufacturing cost or cost per unit load supply	0	1	2	3	4	5
						Delivery on time, potential for cycle time or lead time reduction	0	1	2	3	4	5
						Specified Quality, quality management system of supplier.	0	1	2	3	4	5
						Technological capability (manufacturing facilities and capabilities, productivity, innovation, knowledge workers, documentation)	0	1	2	3	4	5
						Financial capability (ability for further investment, return on investment (ROI), healthy net present value (NPV))	0	1	2	3	4	5
						Flexibility (variety in raw materials or components, ability to produce/supply under make-to-order or assemble-to-order environments, facility planning, etc.)	0	1	2	3	4	5
						Organization & control (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	0	1	2	3	4	5
						Services and communications with the supplier (able to provide after services on time, ensure reliability)	0	1	2	3	4	5
						Any other indicator you consider: please specify	0	1	2	3	4	5
Conserved/preserved Environmental aspects	1	2	3	4	5	Concern about preservation of environment						
						Attainment of sustainable environmental competencies	0	1	2	3	4	5
						Environmental management system (carry out environmental impact assessment (EIA) periodically, reporting to the customer, etc.	0	1	2	3	4	5
						Any other indicator you consider: please specify	0	1	2	3	4	5
Healthy/sound Social aspects	1	2	3	4	5	Ability to develop long-term relationships with customer						
						Social- responsibilities (following professional/engineering ethics, help building social institutions, not using child labor, etc.)	0	1	2	3	4	5
						Work safety & labor health	0	1	2	3	4	5
						Any other indicator you consider: please specify	0	1	2	3	4	5

Notes: Not Considered = (0); Weak Importance = (1); Low Moderate Importance = (2); Moderate Importance = (3); Strong Importance = (4); Extreme Importance = (5)

Relative importance of attributes being attached for supplier selection in manufacturing/assembling of company products

Please write down the name of the product(s) that are relevant to sustainable economic, environmental and social aspects: ....Aluminium...alloy_3003........

Please encircle on the box you find appropriate.

Main Criteria (indicators)	Importance being attached by the company	Sub-criteria (indicators)	Importance being attached by the company
Sustainable Economic aspects	1 2 3 4 5	Economic aspects	
		Constant reduction of manufacturing cost or cost per unit load supply	0 1 2 3 4 5
		Delivery on time, potential for cycle time or lead time reduction	0 1 2 3 4 5
		Specified Quality, quality management system of supplier.	0 1 2 3 4 5
		Technological capability (manufacturing facilities and capabilities, productivity, innovation, knowledge workers, documentation)	0 1 2 3 4 5
		Financial capability (ability for further investment, return on investment (ROI), healthy net present value (NPV))	0 1 2 3 4 5
		Flexibility (variety in raw materials or components, ability to produce/supply under make-to-order or assemble-to-order environments, facility planning, etc.)	0 1 2 3 4 5
		Organization & control (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	0 1 2 3 4 5
		Services and communications with the supplier (able to provide after services on time, ensure reliability)	0 1 2 3 4 5
		Any other indicator you consider: please specify	0 1 2 3 4 5
Conserved/preserved Environmental aspects	1 2 3 4 5	Concern about preservation of environment	
		Attainment of sustainable environmental competencies	0 1 2 3 4 5
		Environmental management system (carry out environmental impact assessment (EIA) periodically, reporting to the customer, etc.	0 1 2 3 4 5
		Any other indicator you consider: please specify	0 1 2 3 4 5
Healthy/sound Social aspects	1 2 3 4 5	Ability to develop long-term relationships with customer	
		Social- responsibilities (following professional/engineering ethics, help building social institutions, not using child labor, etc.)	0 1 2 3 4 5
		Work safety & labor health	0 1 2 3 4 5
		Any other indicator you consider: please specify	0 1 2 3 4 5

Notes: Not Considered = (0); Weak Importance = (1); Low Moderate Importance = (2); Moderate Importance = (3); Strong Importance = (4); Extreme Importance = (5)

Relative importance of attributes being attached for supplier selection in manufacturing/assembling of company products

Please write down the name of the product(s) that are relevant to sustainable economic, environmental and social aspects: ....Aluminium....alloy_3003........

Please encircle on the box you find appropriate.

Main Criteria (indicators)	Importance being attached by the company	Sub-criteria (indicators)	Importance being attached by the company
Sustainable Economic aspects	1 2 3 4 5	Economic aspects	
		Constant reduction of manufacturing cost or cost per unit load supply	0 1 2 3 4 5
		Delivery on time, potential for cycle time or lead time reduction	0 1 2 3 4 5
		Specified Quality, quality management system of supplier.	0 1 2 3 4 5
		Technological capability (manufacturing facilities and capabilities, productivity, innovation, knowledge workers, documentation)	0 1 2 3 4 5
		Financial capability (ability for further investment, return on investment (ROI), healthy net present value (NPV))	0 1 2 3 4 5
		Flexibility (variety in raw materials or components, ability to produce/supply under make-to-order or assemble-to-order environments, facility planning, etc.)	0 1 2 3 4 5
		Organization & control (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	0 1 2 3 4 5
		Services and communications with the supplier (able to provide after services on time, ensure reliability)	0 1 2 3 4 5
		Any other indicator you consider: please specify	0 1 2 3 4 5
Conserved/preserved Environmental aspects	1 2 3 4 5	Concern about preservation of environment	
		Attainment of sustainable environmental competencies	0 1 2 3 4 5
		Environmental management system (carry out environmental impact assessment (EIA) periodically, reporting to the customer, etc.	0 1 2 3 4 5
		Any other indicator you consider: please specify	0 1 2 3 4 5
Healthy/sound Social aspects	1 2 3 4 5	Ability to develop long-term relationships with customer	
		Social- responsibilities (following professional/engineering ethics, help building social institutions, not using child labor, etc.)	0 1 2 3 4 5
		Work safety & labor health	0 1 2 3 4 5
		Any other indicator you consider: please specify	0 1 2 3 4 5

Notes: Not Considered = (0); Weak Importance = (1); Low Moderate Importance = (2); Moderate Importance = (3); Strong Importance = (4); Extreme Importance = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A1 - D1

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A1 - D2

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A1- D3

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A2-D1

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
	1	2	3	4	5
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A2 - D2

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A2-D3

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A3 - D1

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A3_D2

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A3_D3

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A4-D1

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A4-D2

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A4-D3

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A5 - D1

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A5_D2

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A5-D3

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A6-D1

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A6-D2

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A6 - D3

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
	1	2	3	4	5
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A7- D1

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A7- D2

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A7-D3

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A8- D1

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A8 - D2

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier Company name... A8 - D3

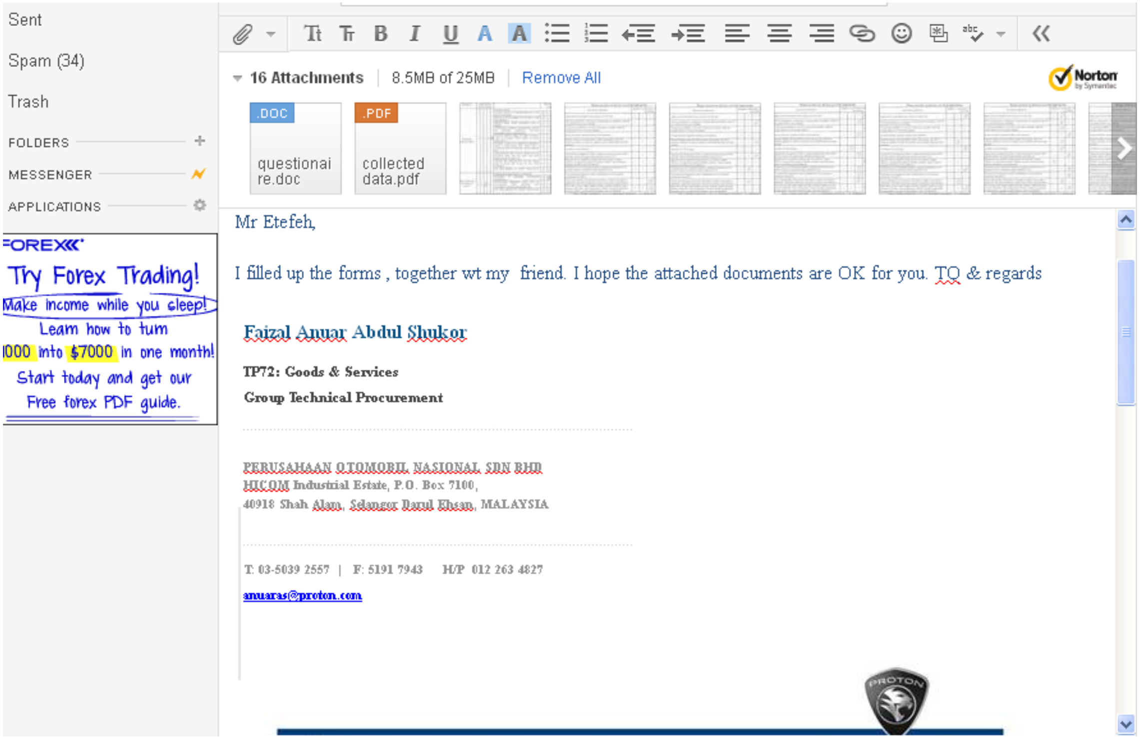
Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control)	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

Appendix-C : The collected data for the second test bed (Proton Company)

Correspondence for data collection



Relative importance of indicators being attached for supplier selection in manufacturing/assembling of company products

Please write down the name of the product(s) that are relevant to sustainable economic, environmental and social aspects: ..Battery..

Please encircle on the box you find appropriate.

Main Criteria (indicators)	Importance being attached by the company					Sub-criteria (indicators)	Importance being attached by the company					
Sustainable Economic aspects	1	2	3	4	5	Economic aspects						
						Constant reduction of manufacturing cost or cost per unit load supply	0	1	2	3	4	5
						Delivery on time, potential for cycle time or lead time reduction	0	1	2	3	4	5
						Specified Quality, quality management system of supplier.	0	1	2	3	4	5
						Technological capability (manufacturing facilities and capabilities, productivity, innovation, knowledge workers, documentation)	0	1	2	3	4	5
						Financial capability (ability for further investment, return on investment (ROI), healthy net present value (NPV))	0	1	2	3	4	5
						Flexibility (variety in raw materials or components, ability to produce/supply under make-to-order or assemble-to-order environments, facility planning, etc.)	0	1	2	3	4	5
						Organization & control (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	0	1	2	3	4	5
						Services and communications with the supplier (able to provide after services on time, ensure reliability)	0	1	2	3	4	5
						Any other indicator you consider: please specify	0	1	2	3	4	5
Conserved/preserved Environmental aspects	1	2	3	4	5	Concern about preservation of environment						
						Attainment of sustainable environmental competencies	0	1	2	3	4	5
						Environmental management system (carry out environmental impact assessment (EIA) periodically, reporting to the customer, etc.	0	1	2	3	4	5
						Any other indicator you consider: please specify	0	1	2	3	4	5
Healthy/sound Social aspects	1	2	3	4	5	Ability to develop long-term relationships with customer						
						Social- responsibilities (following professional/engineering ethics, help building social institutions, not using child labor, etc.)	0	1	2	3	4	5
						Work safety & labor health	0	1	2	3	4	5
						Any other indicator you consider: please specify	0	1	2	3	4	5

Notes: Not Considered = (0); Weak Importance = (1); Low Moderate Importance = (2); Moderate Importance = (3); Strong Importance = (4); Extreme Importance = (5)

Relative importance of indicators being attached for supplier selection in manufacturing/assembling of company products

Please write down the name of the product(s) that are relevant to sustainable economic, environmental and social aspects: …………Battery…………………………………

Please encircle on the box you find appropriate.

Main Criteria (indicators)	Importance being attached by the company					Sub-criteria (indicators)	Importance being attached by the company					
Sustainable Economic aspects	1	2	3	4	5	Economic aspects						
						Constant reduction of manufacturing cost or cost per unit load supply	0	1	2	3	4	5
						Delivery on time, potential for cycle time or lead time reduction	0	1	2	3	4	5
						Specified Quality, quality management system of supplier.	0	1	2	3	4	5
						Technological capability (manufacturing facilities and capabilities, productivity, innovation, knowledge workers, documentation)	0	1	2	3	4	5
						Financial capability (ability for further investment, return on investment (ROI), healthy net present value (NPV))	0	1	2	3	4	5
						Flexibility (variety in raw materials or components, ability to produce/supply under make-to-order or assemble-to-order environments, facility planning, etc.)	0	1	2	3	4	5
						Organization & control (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	0	1	2	3	4	5
						Services and communications with the supplier (able to provide after services on time, ensure reliability)	0	1	2	3	4	5
						Any other indicator you consider: please specify ………………………………	0	1	2	3	4	5
Conserved/preserved Environmental aspects	1	2	3	4	5	Concern about preservation of environment						
						Attainment of sustainable environmental competencies	0	1	2	3	4	5
						Environmental management system (carry out environmental impact assessment (EIA) periodically, reporting to the customer, etc.	0	1	2	3	4	5
						Any other indicator you consider: please specify ………………………………	0	1	2	3	4	5
Healthy/sound Social aspects	1	2	3	4	5	Ability to develop long-term relationships with customer						
						Social- responsibilities (following professional/engineering ethics, help building social institutions, not using child labor, etc.)	0	1	2	3	4	5
						Work safety & labor health	0	1	2	3	4	5
						Any other indicator you consider: please specify ………………………………	0	1	2	3	4	5

Notes: Not Considered = (0); Weak Importance = (1); Low Moderate Importance = (2); Moderate Importance = (3); Strong Importance = (4); Extreme Importance = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S1-A

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S L -A

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S3-A

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S4-A

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
	1	2	3	4	5
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: SS_A

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S6-A

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S1-B

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S2-B

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S3-B

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S9-B

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

Supplier company name: S5-B

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

A Supplier's performances for a specified product from sustainable point of view

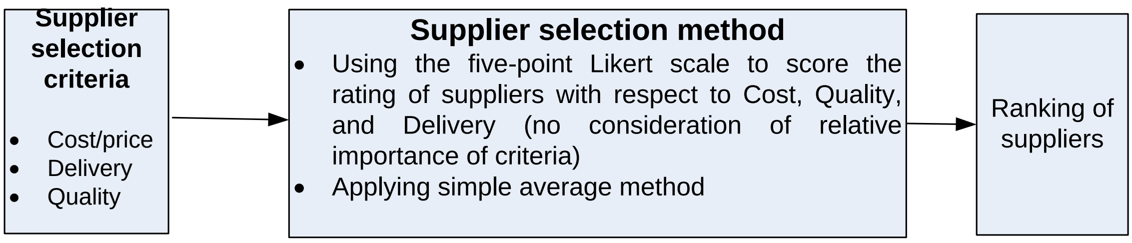
Supplier company name: S6-B

Please encircle on the box you find appropriate.

Sub-criteria (indicators)	Supplier's performance with respect to sub-criteria				
Supply items at reasonable costs or prices over the years	1	2	3	4	5
Delivery performance (consistency in meeting delivery deadlines, order fill rate, perfect delivery rate, labeling)	1	2	3	4	5
Lot rejection rate(PPM) or rework or scrap rate is normally within the average quality level in the past supplies	1	2	3	4	5
Having technically adequate employee and equipment	1	2	3	4	5
Financial stability (assets and debts, income and earnings, cash flow), Financial capability to reach raw material, semi-finished product and other resources	1	2	3	4	5
Flexibility of order altering	1	2	3	4	5
Organizational management (follows standard operating procedure (SOP), clear flow charts with control loops and their execution, etc.)	1	2	3	4	5
Integrated service capability (response time for customers' request, efficiency of engineering support, fulfilling customers' special requests, customer information service platform)	1	2	3	4	5
Conformance to environmental regulatory standards (promoting level of pollution control to maximum Europe standard (EUV)),	1	2	3	4	5
Environmental management system (establishment of environmental commitment and policy)	1	2	3	4	5
Social- responsibilities (the interests and rights of employee, the rights of stakeholder, information disclosure, respect for the policy, discrimination)	1	2	3	4	5
Work safety & labor health (health and safety incidents, health and safety practices, child labor, long working hours, flexible working arrangements, job opportunities, research and development, career development)	1	2	3	4	5

Notes: Weakly performed = (1); Low Moderately performed = (2); Moderately performed = (3); Strongly performed = (4); Extremely performed = (5)

Appendix-D: Existing practices for supplier selection in the two mentioned companies



Appendix-E: The written MATLAB programming for the proposed FIS-DEA method

clear all; clc

######### **Fuzzy set definitions for weights**

WI= [0 0.167 0.334]; LMI= [0.167 0.334 0.5]; MI= [0.334 0.5 0.667]; SI= [0.5 0.667 0.834]; EI= [0.667 0.834 1];

#########

######### **Identify the weights of criteria and sub-criteria for Imen Soukht Sepahan Company**

W= [EI EI MI; EI SI MI; EI MI MI];

WSC=[EI EI EI;EI SI SI;EI EI SI;SI SI MI; MI MI LMI; LMI LMI LMI;MI MI MI;SI MI LMI;SI MI MI; EI SI MI; MI MI LMI;LMI LMI LMI];

#########

######### **Identify the weights of criteria and sub-criteria for Proton Company**

EI=[4/6 5/6 1]; W=[EI EI;MI SI;LMI LMI];

WSC=[EI EI;SI EI;EI EI;MI SI;MI MI;SI MI;MI SI;SI SI;LMI MI;MI SI;LMI LMI;LMI MI];

#########

########## **Process on the weights**

```
[i j]=size (W); [i1 j1]=size (WSC); x = 0:0.00001:1;
  for k=1:i1
        for n=1:j1
            if k<=8
            WSCM (k,n)=WSC(k,n)*W(1,n);
            else if k<=10
             WSCM (k,n)=WSC(k,n)*W(2,n);
```

```
            else
               WSCM (k,n)=WSC(k,n)*W(3,n);
            end
        end
   end
for n=1:j1/3
    a1=(WSCM(1,3*n-2)+WSCM(2,3*n-2)+WSCM(3,3*n-2)+WSCM(4,3*n-
2)+WSCM(5,3*n-2)+WSCM(6,3*n-2)+WSCM(7,3*n-2)+WSCM(8,3*n-
2)+WSCM(9,3*n-2) )/8;
   C(1,3*n-2)=a1;
   a2=(WSCM(1,3*n-1)+WSCM(2,3*n-1)+WSCM(3,3*n-1)+WSCM(4,3*n-
1)+WSCM(5,3*n-1)+WSCM(6,3*n-1)+WSCM(7,3*n-1)+WSCM(8,3*n-1))/8;
   C(1,3*n-1)=a2;

a3=(WSCM(1,3*n)+WSCM(2,3*n)+WSCM(3,3*n)+WSCM(4,3*n)+WSCM(5,3*n)+
WSCM(6,3*n)+WSCM(7,3*n)+WSCM(8,3*n))/8;
   C (1,3*n)=a3;
   end
  for n=1:j1/3
    a1= (WSCM (9, 3*n-2) +WSCM (10,3*n-2))/2;
   C (2, 3*n-2)=a1;
   a2= (WSCM (9, 3*n-1) +WSCM (10,3*n-1))/2;
   C(2,3*n-1)=a2;
    a3= (WSCM (9, 3*n)+WSCM(10,3*n))/2;
   C (2, 3*n)=a3;
   end
```

```
for n=1:j1/3
    a1= (WSCM (11, 3*n-2) +WSCM (12, 3*n-2))/2;
   C (3, 3*n-2) =a1;
   a2= (WSCM (11, 3*n-1) +WSCM (12, 3*n-1))/2;
   C (3, 3*n-1) =a2;
    a3= (WSCM (11, 3*n) +WSCM (12,3*n))/2;
   C (3, 3*n) =a3;
  end
 for k=1:i
    for n=1:j1/3;
        l=3*n;
        o=1+3*(n-1);
       mi = C(k, o:l);
       mi=trimf (x, mi);
       mi =defuzz (x, mi, 'centroid');
      NI (n)=mi;
    end
    KI(k,:)=NI;
 End
##########
```

########## **Calculate the weight restrictions (u1/u2),(u2/u3),(u1/u3)**

```
KI1=transpose (KI); [i,j]=size (KI1);
for k=1:j-1
    for n=1:i;
am(n ,k)=KI1(n ,k)/KI1(n,k+1);
    end
```

```
end
for k=1:j-2
    for n=1:i;
am(n,k+2)=KI1(n ,k)/KI1(n ,k+2);
    end
end
A=min (am); B=max (am);
##########
```

########## **Fuzzy set definitions for suppliers' performances**

```
WP= [0 10/6 20/6]; LMP= [10/6 20/6 30/6]; MP= [20/6 30/6 40/6];
SP= [30/6 40/6 50/6]; EP= [40/6 50/6 10];
##########
```

########## **Prepare of the inputs for FIS-DEA approach**

```
for i=1:M;
X = input ('please import the information supplier 1 to evaluation):','s');
I1=eval(X); [i2 j2]=size (I1);
for n=1:i2
    a1= (I1 (n, 1) +I1 (n, 4) + I1 (n, 7))/3;    Ia(n,1)=a1;
   a2= (I1 (n, 2) +I1 (n, 5) + I1 (n, 8))/3;    Ia(n,2)=a2;
   a3= (I1 (n, 3)+I1(n,6)+I1(n,9))/3;    Ia(n,3)=a3;
   end
   I(:,(3*i-2):(3*i))=Ia;
end
   J=I; [ie je]=size (J); x = 0:0.0001:10;
 for k=1:ie
    for n=1:je/3;
```

```
      l=3*n;
      o=1+3*(n-1);
     mi=J(k,o:l);      mi=trimf(x, mi);      mi =defuzz(x,mi,'centroid');
    NIF (n) = mi;
  end
  KIF (k, :) =NIF;
end
 KIF=transpose (KIF);
##########
```

########## **Getting the sustainability affinity indices**

```
CC1=readfis('economic2-1'); CC2=readfis('economic2_2');
CC3=readfis('economic2_3'); CC4=readfis('economic2_4');
CC5=readfis('economic21'); CC6=readfis('economic22');
CC7=readfis('economic2'); CC8=readfis('enviromental2');
CC9=readfis('social2'); getfis(CC1); getfis(CC2); getfis(CC3);
getfis(CC4); getfis(CC5); getfis(CC6); getfis(CC7); getfis(CC8);
getfis(CC9);
economic2_1=evalfis(KIF(:,1:2),CC1); economic2_2=evalfis(KIF(:,3:4),CC2);
economic2_3=evalfis(KIF(:,5:6),CC3); economic2_4=evalfis(KIF(:,7:8),CC4);
economic21=evalfis([economic2_1 economic2_2],CC5);
economic22=evalfis([economic2_3 economic2_4],CC6);
economic2=evalfis([economic21 economic22],CC7);
enviromental2=evalfis(KIF(:,9:10),CC8); social2=evalfis(KIF(:,11:12),CC9);
output =[economic2 enviromental2  social2];
outputn= output/max(max(output));
##########
```

Appendix-F : The written Lingo programming the proposed FIS-DEA method

```
MODEL:
! Data Envelope Analysis of Decision Maker Efficiency;
 SETS:
  DMU/B1 B2 B3 B4 B5 B6 /: %%% Depending on the number of suppliers
   EFFICIENCY; ! Each decision making unit has a;
    FACTOR/DMU c1 c2 c3 /;! Economic Environmental Social/;
! There is a set of factors, input & output;
  DXF( DMU, FACTOR):  F; ! F( I, J) = Jth factor of DMU I;
 ENDSETS
 DATA: ! Inputs are spending/pupil, % not low income;
! Outputs are Writing score and Science score;
  NINPUTS = 1;  ! The first NINPUTS factors are inputs;
F=   1    0.7002     0.8001     0.6
     1    0.6005     0.6        0.4
     1    0.4999     0.5        0.5
     1    0.4        0.6        0.3999
     1    0.3        0.3999     0.3
     1    0.2008     0.3        0.2001
   ENDDATA
! The Model;
 SETS:
   ! Weights used to compute DMU I's score;
   DXFXD(DMU,FACTOR) : W;
 ENDSETS
```

```
! Try to make everyone's score as high as possible;
  MAX = @SUM( DMU: EFFICIENCY);
! The LP for each DMU to get its score;
  @FOR( DMU( I):
   EFFICIENCY ( I) = @SUM( FACTOR(J)|J #GT# NINPUTS:
    F(I, J)* W(I, J));
! Sum of inputs (denominator) = 1;
  ! @SUM ( FACTOR ( J) | J #LE# NINPUTS:
    F( I, J)* W( I, J)) = 1;!
! Using DMU I's weights, no DMU can score better than 1;
 @FOR( DMU( K) |  k #NE# 1 #AND# k #NE# 5:
   @SUM( FACTOR(J)|J #GT# NINPUTS:
    F(K, J)* W(I, J)) <= 1;
W(K,3)<=(1/1.4688)*W(I,2);
W(K,3)>=(1/2.4643)*W(I,2);
W(K,4)<=(1/3.8015)*W(I,2);
W(K,4)>=(1/4.3125)*W(I,2);
W(K,4)<=(1/1.75)*W(I,3);
W(K,4)>=(1/2.5882)*W(I,3);
);   );
! The weights must be greater than zero;
 !@FOR( DXFXD( I, J): @BND( .00001, X, 100000));
END
```

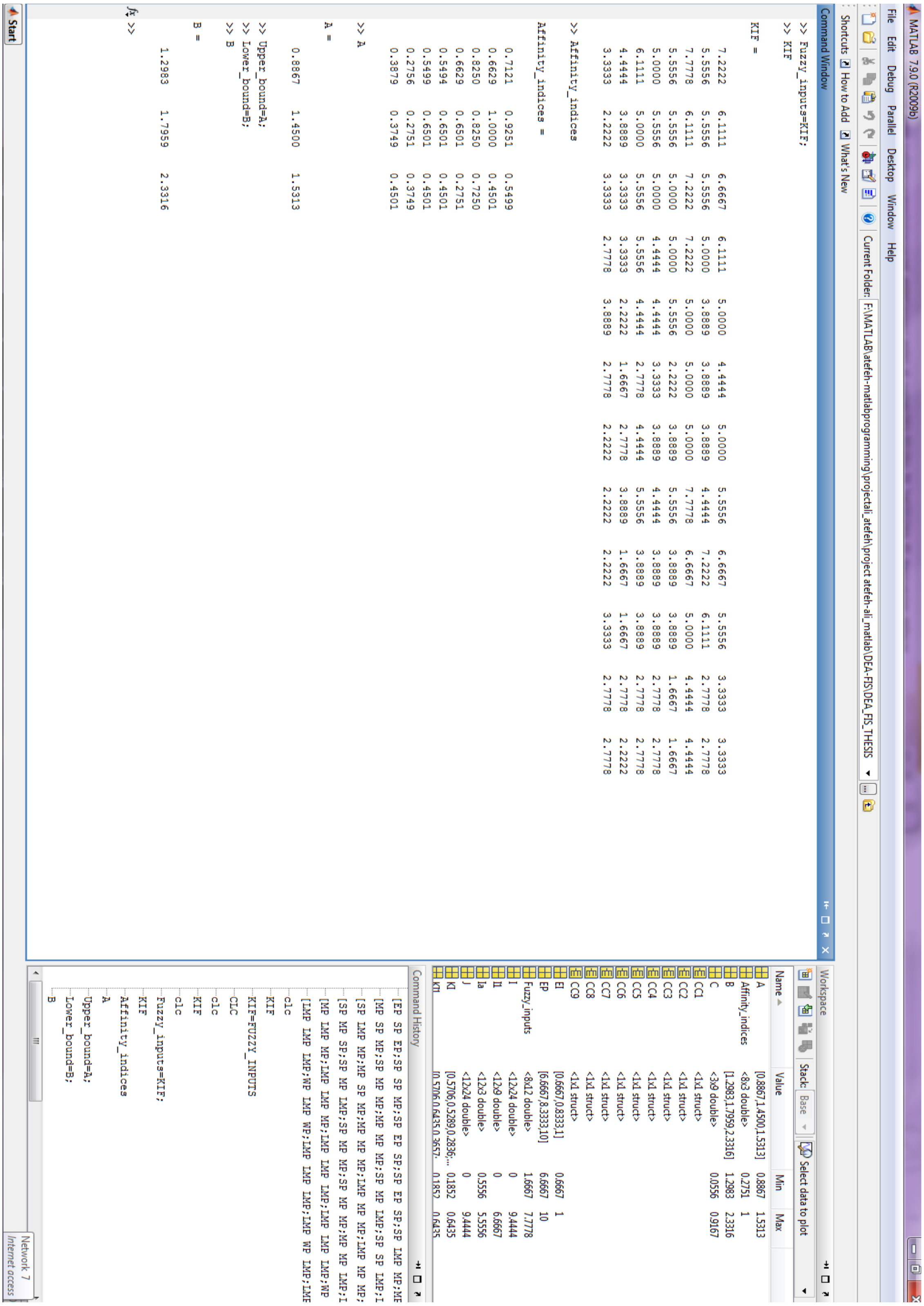
Appendix-G: The written Lingo programming of the conventional DEA method

```
MODEL:
! Data Envelope Analysis of Decision Maker Efficiency;
 SETS:
  DMU/B1 B2 B3 B4 B5 B6 /: %%% Depending on the number of suppliers
   EFFICIENCY; ! Each decision making unit has a;
    FACTOR/DMU c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 /;! Sub-criteria/;
! There is a set of factors, input & output;
  DXF (DMU, FACTOR):  F; ! F (I, J) = Jth factor of DMU I;
 ENDSETS
 DATA: ! Inputs are spending/pupil, % not low income;
! Outputs are writing score and Science score;
  NINPUTS = 1;  ! The first NINPUTS factors are inputs;

F=
1   1    1    1    0.9  0.8  0.7  0.8  1    0.8  1    0.6  0.7
1   1    0.7  1    0.7  0.6  0.7  0.6  0.9  0.5  0.8  0.4  0.6
1   0.8  0.6  0.8  0.6  0.7  0.4  0.6  0.8  0.5  0.6  0.5  0.7
1   0.6  0.7  0.9  0.6  0.4  0.5  0.6  0.8  0.5  0.8  0.4  0.5
1   0.4  0.5  0.5  0.5  0.3  0.4  0.5  0.3  0.4  0.5  0.3  0.4
1   0.5  0.4  0.5  0.3  0.3  0.2  0.4  0.4  0.3  0.3  0.2  0.2
ENDDATA
! The Model;
 SETS:
   ! Weights used to compute DMU I's score;
```

```
  DXFXD(DMU,FACTOR) : W;
 ENDSETS
! Try to make everyone's score as high as possible;
  MAX = @SUM( DMU: EFFICIENCY);
! The LP for each DMU to get its score;
  @FOR( DMU( I):
   EFFICIENCY ( I) = @SUM( FACTOR(J)|J #GT# NINPUTS:
    F(I, J)* W(I, J));
! Sum of inputs (denominator) = 1;
  ! @SUM ( FACTOR ( J) | J #LE# NINPUTS:
    F( I, J)* W( I, J)) = 1;!
! Using DMU I's weights, no DMU can score better than 1;
 @FOR( DMU( K) |  :
   @SUM( FACTOR(J)|J #GT# NINPUTS:
    F(K, J)* W(I, J)) <= 1;
);   );
! The weights must be greater than zero;
 !@FOR( DXFXD( I, J): @BND( .00001, X, 100000));
END
```

Appendix-H: A sample result provided by MATLAB programming



Appendix-I: A sample result provided by Lingo programming

Global optimal solution found.
Objective value: 4.036043
Infeasibilities: 0.1665335E-15
Total solver iterations: 63

Variable	Value	Reduced Cost
NINPUTS	1.000000	0.000000
EFFICIENCY(B1)	0.7217412	0.000000
EFFICIENCY(B2)	0.5733282	0.000000
EFFICIENCY(B3)	0.5000292	0.000000
EFFICIENCY(B4)	0.4701074	0.000000
EFFICIENCY(B5)	0.3350409	0.000000
EFFICIENCY(B6)	0.2354856	0.000000
EFFICIENCY(B7)	0.2003101	0.000000
EFFICIENCY(B8)	1.000000	0.000000
F(B1, DMU)	1.000000	0.000000
F(B1, ECONOMIC)	0.7002000	0.000000
F(B1, ENVIRONMENTAL)	0.8001000	0.000000
F(B1, SOCIAL)	0.6000000	0.000000
F(B2, DMU)	1.000000	0.000000
F(B2, ECONOMIC)	0.6005000	0.000000
(B2, ENVIRONMENTAL)	0.6000000	0.000000
F(B2, SOCIAL)	0.4000000	0.000000
F(B3, DMU)	1.000000	0.000000
F(B3, ECONOMIC)	0.4999000	0.000000
F(B3, ENVIRONMENTAL)	0.5000000	0.000000
F(B3, SOCIAL)	0.5000000	0.000000
F(B4, DMU)	1.000000	0.000000
F(B4, ECONOMIC)	0.4000000	0.000000
(B4, ENVIRONMENTAL)	0.6000000	0.000000
F(B4, SOCIAL)	0.3999000	0.000000
F(B5, DMU)	1.000000	0.000000
F(B5, ECONOMIC)	0.3000000	0.000000
F(B5, ENVIRONMENTAL)	0.3999000	0.000000
F(B5, SOCIAL)	0.3000000	0.000000
F(B6, DMU)	1.000000	0.000000
F(B6, ECONOMIC)	0.2008000	0.000000
(B6, ENVIRONMENTAL)	0.3000000	0.000000
F(B6, SOCIAL)	0.2001000	0.000000
F(B7, DMU)	1.000000	0.000000
F(B7, ECONOMIC)	0.2004000	0.000000
F(B7, ENVIRONMENTAL)	0.2001000	0.000000
F(B7, SOCIAL)	0.2001000	0.000000
F(B8, DMU)	1.000000	0.000000
F(B8, ECONOMIC)	0.9997000	0.000000
B8, ENVIRONMENTAL)	1.000000	0.000000
F(B8, SOCIAL)	1.000000	0.000000
W(B1, DMU)	0.000000	0.000000
W(B1, ECONOMIC)	0.5145148	0.000000
W(B1, ENVIRONMENTAL)	0.3502960	0.000000
W(B1, SOCIAL)	0.1353435	0.000000
W(B2, DMU)	0.000000	0.000000
W(B2, ECONOMIC)	0.5836688	0.000000
W(B2, ENVIRONMENTAL)	0.2811628	0.000000
W(B2, SOCIAL)	0.1353435	0.000000
W(B3, DMU)	0.000000	0.000000
W(B3, ECONOMIC)	0.5836688	0.000000
W(B3, ENVIRONMENTAL)	0.2811628	0.000000
W(B3, SOCIAL)	0.1353435	0.000000
W(B4, DMU)	0.000000	0.000000
W(B4, ECONOMIC)	0.5145148	0.000000

W(B4, ENVIRONMENTAL)	0.3502960	0.000000
W(B4, SOCIAL)	0.1353435	0.000000
W(B5, DMU)	0.000000	0.000000
W(B5, ECONOMIC)	0.5145148	0.000000
(B5, ENVIRONMENTAL)	0.3502960	0.000000
W(B5, SOCIAL)	0.1353435	0.000000
W(B6, DMU)	0.000000	0.000000
W(B6, ECONOMIC)	0.5145148	0.000000
W(B6, ENVIRONMENTAL)	0.3502960	0.000000
W(B6, SOCIAL)	0.1353435	0.000000
W(B7, DMU)	0.000000	0.000000
W(B7, ECONOMIC)	0.5836688	0.000000
(B7, ENVIRONMENTAL)	0.2811628	0.000000
W(B7, SOCIAL)	0.1353435	0.000000
W(B8, DMU)	0.000000	0.000000
W(B8, ECONOMIC)	0.5836688	0.000000
B8, ENVIRONMENTAL)	0.2811628	0.000000
W(B8, SOCIAL)	0.1353435	0.000000

Appendix-J: Publications from this research

Published Journal papers

Amindoust, A., Ahmed, S., Saghafinia, A.,(2012), 2013, "Using Data Envelopment Analysis for Green Supplier Selection in Manufacturing under Vague Environment", *Advanced Materials Research*, Publisher's name (Trans Tech Publications), Publisher's URL { http://www.scientific.net/AMR}, Volume 622-623, Pages 1682-1685, **ISI-Cited** Publication.

Amindoust, A., Ahmed, S., Saghafinia, A., (2012), 2012,"Location Decision of Supply Chain Management in the Automotive Industry", *The International Journal of Engineering and Applied Sciences (EAAS)*, Publisher's name (ARF Printing), Publisher's URL {http://eaas-journal.org/otherinfo/Volume-1/546/534}, Volume 1,Issue 2, Pages 064-067.

Amindoust, A., Ahmed, S., Saghafinia, A. (2012), 2012,"A Taxonomy and Review on Supplier Selection Methods under Uncertainty", *The International Journal of Information Technology & Management (JITBM)*, Publisher's name (ARF Sourcing Islamabad), Publisher's URL { http://www.jitbm.com/volume7.html }, Volume 7,Issue 1, Pages 033-043.

Amindoust, A., Ahmed, S., Saghafinia, A., (2012), 2012 "Supplier performance measurement of palm oil industries from a sustainable point of view in Malaysia", *Biotechnology An Indian journal*, Publisher's name (Trade Science Inc.), Publisher's URL { http://tsijournals.com/bcaij/BCAIJ_TOC.htm}, Volume 6,Issue 6, Pages 155-158.

Amindoust, A., Ahmed, S., Saghafinia, A., (2012), 2011"Supplier Selection and Performance Evaluation of Telecommunication Company", *American Journal of Engineering and Applied Sciences*, Publisher's name (Science Publications), Publisher's URL { http://thescipub.com/abstract/10.3844/ajeassp.2012.49.52}, Volume 5, Issue 1, Pages 49-52.

Atefeh Amindoust, Shamsuddin Ahmed, Ali Saghafinia and Ardeshir Bahreininejad, (2012) 2011, "Sustainable supplier selection: a ranking model based on fuzzy inference system", *Applied Soft Computing*, Publisher's name (Elsevier), Publisher's URL { http://www.elsevier.com/locate/asoc}, Volume 12, Issue 6, Pages 1668-1677, **ISI-Cited Publication-Q1**.

Submitted Journal paper

Amindoust, A., Ahmed, S., Saghafinia, A., Emrouznejad, A.," An integrated FIS-DEA approach for sustainable supplier selection under uncertainty", *Applied Soft Computing*, Publisher's name (Elsevier), Publisher's URL { http://www.elsevier.com/locate/asoc}, (**ISI-Cited publications-Q1).**

Conferences

Amindoust, A., Ahmed, S., Saghafinia, A.," Integration of Social Merits into the Management of Supply Chain: A Case Study of Steel Manufacturing in Iran", National Research & Innovation Conference for Graduate Students in Social Sciences (GS-NRIC 2012), 7-9 December Melaka, Malaysia.

Amindoust, A., Ahmed, S.,"A survey of mathematical programming based approaches in supplier", Asia-Oceania Top University League on Engineering (AOTULE 2012), 24-25 November, Kuala Lumpur, Malaysia.

Amindoust, A., Ahmed, S., Saghafinia, A.," Supplier (ISP) selection and evaluation based on mathematical model", Asia-Oceania Top University League on Engineering (AOTULE 2012), 24-25 November, Kuala Lumpur, Malaysia.

Amindoust, A., Ahmed, S., Saghafinia, A., "Supplier selection in Electrical &Electronic industry from a sustainable point of view", The 2nd World Sustainability Forum, e-conferences, 1-30 November2012, Publisher's name (MDPI AG), Publisher's URL {http://www.sciforum.net/conf/wsf2}.

Amindoust, A., Ahmed, S., Saghafinia, A.," Using data envelopment analysis for green supplier selection in manufacturing under vague environment", International Conference on Manufacturing and Optimization (ICMO), 15-16 September Beijing, china.

Amindoust, A., Ahmed, S., Saghafinia, A., "Applying a mathematical model for green supply chain management", the International Conference on Mechanical Engineering and Renewable Energy (ICMERE2011), 22-24 December 2011, Chittagong, Bangladesh.

Amindoust, A., Ahmed, S., Saghafinia, A., "Supply chain management: supplier selection and performance evaluation" The UMIES conference, Malaysia Kuala Lumpur, July 2011.

Amindoust, A., Ahmed, S., Saghafinia, A., "Fuzzy theory applied in supplier selection problem: A taxonomic sample" The First Iranian Students scientific conference, Malaysia Kuala Lumpur, April 2011.

A. Amindoust, Shamsudin Ahmed, S. Ketabi, "Evaluation and Selection of Supplier in Supply Chain Network Based on DEA" APIEMS conference, Melaka, Malaysia2010.